1973

A Study of Energy and Water Transfer in Irrigated and Nonirrigated Sorghum

Loyd Raymond Stone

A STUDY OF ENERGY AND WATER TRANSFER IN IRRIGATED AND NONIRRIGATED SORGHUM

BY

LOYD RAYMOND STONE

A thesis submitted
in partial fulfillment of the requirements for the
degree Doctor of Philosophy, Major in
Agronomy, South Dakota
State University

1973

A STUDY OF ENERGY AND WATER TRANSFER IN IRRIGATED AND NONIRRIGATED SORGHUM

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Doctor of Philosophy, and is acceptable as meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

A STUDY OF ENERGY AND WATER TRANSFER IN

IRRIGATED AND NONIRRIGATED SORGHUM

Abstract

LOYD RAYMOND STONE

Under the supervision of Dr. Maurice L. Horton

Approximately 70% of all precipitation is lost through percolation out of the root zone or by evapotranspiration (evaporation from the soil plus transpiration from plants). Estimation of these water loss processes has generally been on a small scale due to the cost and time required for their measurement. Development of remote thermal scanners has provided a possible means of estimating water loss from surfaces by using the surface temperature. This study was designed (a) to determine water movement patterns in the soil profile and (b) to evaluate the feasibility of using canopy temperatures in estimating evapotranspiration rates from cropped areas.

Soil water flux values were estimated using tensiometer data in both the irrigated and nonirrigated areas. Flux was upward in all soil depth intervals in the nonirrigated area during the study. Flux in the 130-150 cm depth interval remained downward throughout the study in irrigated sorghum. The flux in the 15-30, 30-50, and 50-70 cm depth intervals reversed and became upward within one week following the irrigation of sorghum. If flux out of the root zone had been neglected, and profile water depletion equated with

evapotranspiration (ET), ET would have been overestimated in the irrigated sorghum and underestimated in the nonirrigated sorghum.

Canopy temperature data indicated that the nonirrigated canopy was usually 1-3 C warmer than the irrigated canopy during daylight hours; and that during nighttime, there was no clear temperature difference between canopies. On most dates, the air temperature was warmer than canopy temperature, often by as much as 3-5 C. During the hours of 0000 to 0800 CDT, the canopy temperature was usually warmer than air temperature, often by 5-6 C.

Tensiometer data yielded smaller estimates of evapotranspiration rates than did five microclimate equations used. The equations are for potential ET or have been derived neglecting energy sinks; therefore, their estimates of ET would have been expected to be larger than tensiometer estimates. Two of the five microclimate equations used (Bartholic and Brown), employ the canopy temperature in estimating ET rates. Bartholic ET estimates were found to be approximately 17% smaller than typical ET estimates by the Penman and energy budget-Bowen ratio methods. The Brown method yielded ET rates approximately 22% larger than typical Penman and energy budget-Bowen ratio estimates of ET rates. The Bartholic method requires less input data than the Brown method. Therefore, the Bartholic method is slightly more desirable because of accuracy and less input data required.

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to Dr. M. L. Horton, Associate Professor of Plant Science, for advice, guidance, and assistance given while serving as major adviser during the preparation of this thesis and throughout the graduate work. Appreciation is also extended to the other members of my graduate committee. They are: Dr. R. A. Moore, Dr. T. C. Olson, Professor W. F. Lytle, and Dr. B. E. Hietbrink.

The author is grateful for the association with fellow graduate students, Mr. C. G. Carlson, Mr. J. L. Heilman, and Dr. B. S. Sandhu. The author feels fortunate to have had the capable and dedicated assistance of Mr. Doug Aamold, Mr. John DeWit, Miss Linda Forseth, and Mrs. Nancy Fredrickson during the analysis and plotting of data.

Funds for this study were provided by the Office of Water Resources Research, U. S. Department of Interior, through the South Dakota Water Resources Research Institute and the Plant Science Department of the South Dakota State University Agricultural Experiment Station. Appreciation is extended to Dr. R. C. Ward and the employees of the James Valley Agricultural Research and Extension Center, Redfield, South Dakota, for their assistance during the field study.

Special appreciation is expressed to my wife, Darla, for her support and encouragement during my graduate studies.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

INTRODUCTION

Surface runoff has received much attention because it is the only visible water loss from fields. However, approximately 70% of the average annual precipitation reaching the continental United States is lost by evaporation from the soil, by transpiration from plants, and through percolation out of the root zone (Wadleigh, 1964). Estimates of evapotranspiration (evaporation from soils plus transpiration from plants) and deep percolation (flux) of water from the root zone are difficult to determine, requiring considerable investment of labor and equipment. Barger et al. (1970) stated that water loss by evapotranspiration is the major unknown in studies of the water budget. Evidence is mounting that water flux out of the root zone is more than researchers had formerly thought, particularly under irrigated conditions.

Interest is growing for accurate evapotranspiration estimates for regions, similar to water loss by runoff estimates for large watersheds. With regional evapotranspiration estimates, a water budget analysis for large watershed areas would be more meaningful. Due to the cost and time involvement of equipment and labor, previous evapotranspiration (ET) studies have been on very small and widely separated study areas. The inclusion of this data into an accurate ET network to estimate large-scale water use is not feasible at this time.

The development of remote sensing techniques for detecting parameters of soils and plants that may be related to water deficiency and/or water loss over large regions appears promising. The potential of using aerial thermal scanners to remotely detect soil and canopy temperatures was discussed by Bartholic, Namken, and Wiegand (1972). Research is indicating that the temperature of evaporating surfaces can give indications of the water status of the surfaces. If the surface temperatures determined remotely, or locally in the field, could be used in estimating ET rates, the ability of evaluating losses due to ET locally or over large regions would be enhanced.

A field investigation with irrigated and nonirrigated grain sorghum (Sorghum bicolor (L.) Moench.) was conducted: 1) to determine water movement and loss patterns under various soil water conditions and 2) to evaluate the feasibility of using surface temperatures in estimating evapotranspiration losses from cropped fields.

LITERATURE REVIEW

The water conservation equation for a given volume of plant root zone for a given time period is

$$P + I = R + \Delta W + E + T + D \qquad (1)$$

where P is the precipitation, I is irrigation, R is surface runoff, ΔW is the change in stored water in the soil volume during the time interval, E is evaporation from soil, T is transpiration from the plants, and D is the amount of soil water flow either entering or leaving the soil volume. The measurement of terms in the conservation equation is discussed by Rose (1966). The precipitation, irrigation, runoff, and change in storage terms are readily measurable. The profile drainage, evaporation, and transpiration terms are more difficult to measure.

Between rainfall or irrigation applications, the terms P, I, and R, will equal zero. The water conservation equation then becomes

$$-\Delta W = E + T + D \qquad (2)$$

with the terms previously defined. The change in water storage (ΔW) is found as profile water storage at the end of the time period minus profile water content at the beginning of the period. Equations (1) and (2) are both in the integral form with the terms being totaled over a given period of time. It is often desired to speak of water loss as a rate, or loss per unit of time. Equation (2) expressed in differential form becomes

$$- dW/dt = dE/dt + dT/dt + dD/dt \qquad (3)$$

where W is the water storage in the soil volume and t is time. Equation (3) is the time rate of change form of the water conservation equation between water applications. The rate of evaporation from soil (dE/dt) and the rate of transpiration from plants (dT/dt) are combined to form the evapotranspiration (ET) rate term. The rate of profile water drainage (dD/dt) is commonly referred to as the soil water flux (v). So now equation (3) takes the form

$$- (dW/dt) = ET + v \qquad (4)$$

where (dW/dt) is the rate of water storage change in the soil volume.

The flux term in equation (4) can be estimated using Darcy's equation,

$$v = Ki \qquad (5)$$

where v is the soil water flux, K is the unsaturated hydraulic conductivity, and i is the hydraulic gradient or the driving force (Nielsen et al., 1970). In studies of this nature it is generally assumed that the study area is large enough to have no horizontal movement of water into or out of the soil volume due to horizontal gradients. Thus it is assumed that only vertical flux across the lower boundary caused by hydraulic gradients exists.

Until recently, it was believed that flux of water after an irrigation or rainfall was significant only for the first couple of days following the application. This view has been formed by the acceptance of a "field capacity" term as defined by Veihmeyer and

Hendrickson (1949). Basically the term states that a soil volume will drain until a particular "field capacity" water content is reached. After draining to this point, soil was considered to drain a negligible amount. In the past two decades the errors inherent in this term have been recognized. Hillel (1971) in his text discusses the subjective nature of the term, that it neglects such factors as pre-infiltration wetness of the soil, the depth of wetting, and the amount of water applied.

Using the "field capacity" concept, the change in water storage has been equated with evapotranspiration losses. The assumption of negligible water loss due to flow following irrigation or rainfall has received increasing attention in the past few years. Robins, Pruitt, and Gardner (1954) found measurable downward flux of water from the 0 to 90 cm portion of an alfalfa root zone for 8 days following irrigation. Willardson and Pope (1963) concluded that unsaturated movement of water out of the soil root zone profile, in response to hydraulic potential gradients, is a continuous process. This conclusion appears to exclude the possibility of upward soil water flux into the root zone. Rose and Stern (1965) presented a method for determining the drainage component of the water conservation equation using Darcy's equation and the energy status of soil water, but failed to present actual field data showing the magnitudes possible. Black, Gardner, and Tanner (1970) conducted a field water balance study using snap beans grown on a sandy soil. During the 60-day study period, they estimated total water use at 35 cm;

17 cm due to ET and 18 cm due to drainage from the 150 cm soil profile. Goltz et al. (1971) working with an onion crop on the same sandy soil used by Black et al. (1970) also found drainage exceeding evapotranspiration during their study. In the studies by Black et al. (1970) and Goltz et al. (1971), drainage from the 150 cm soil profile was considerable following water application and then decreased to near zero with time. The low drainage rates resulted from the marked decrease in hydraulic conductivity with decreasing soil water content in the sandy soil. Miller and Aarstad (1971) also concluded that large errors are probable in field measurements of evapotranspiration rates if deep drainage is ignored.

As shown by the literature reports presented above, there has been a realization of the importance soil water flux has in the water conservation equation. It has also been generally considered that upward soil water flow into the plant root zone was possible only in situations where a perched water table existed close to the root zone. Van Bavel, Brust, and Stirk (1968a) inferred that downward flux reversed and became as high as 0.4 cm/day upward into a sorghum root zone. LaRue, Nielsen, and Hagan (1968) estimated an upward soil water flux of 0.01 cm/day into a ryegrass root zone. Stone, Horton, and Olson (1973a) using tensiometer data estimated upward soil water flux rates of 0.2 cm/day into a sorghum root zone. The data presented in the three papers cited in this paragraph clearly illustrate that upward soil water flux into a root zone can and sometimes does occur. Therefore, for accurate use of the water conservation equation, both the magnitude and direction of the soil water flux must be evaluated.

Knowledge of water flux within and into and out of the root zone is important in understanding water movement to plant root extraction volumes and in liquid transport of soluble nutrients. Marshall and Gurr (1954) analyzed the agreement between percent of water lost from a soil volume and the percent of chloride lost by movement from the same volume. The agreement was best at the higher soil water contents and decreased as water content decreased. They theorized that the decrease in chloride movement with associated water loss as soils became drier was due to an increasing amount of water loss due to vapor movement. It might also have been due to salt sieving of chloride anions at lower soil water contents, a fact not discussed in their paper. They did discuss the possibility of negative adsorption increasing the chloride anion concentration in the mobile soil solution, a fact that would have increased the chloride anion movement loss. Doering, Reeve, and Stockinger (1964) estimated evaporation from a field soil using measurements of chloride accumulation in the upper 30 cm. Good agreement was found between the above method and results obtained with an evaporimeter. Their study was conducted on fallow soil with a water table maintained at a depth of 152 cm.

The movement of chloride and nitrate anions was studied by Wetselaar (1961) using three fallow soil profiles. During a drying phase, he found a marked accumulation of both chloride and nitrate anions near the surface (0-5 cm), accompanied by a decrease in the subsurface (5-30 cm). He found the reverse effect, surface depletion and subsurface accumulation of chloride anions, caused by rain. The subsurface did have an increase in nitrates following rainfall, but surface depletion of nitrates was not as clearly indicated as was chloride. He theorized that overall nitrate formation in the 0-30 cm layer, after water application, had prevented observation of nitrate decreases in the 0-5 cm layer. In a later study, Wetselaar (1962) showed the movement capability of chloride and nitrate anions to be approximately equal. The mean downward movement of the anions was approximately 2.5 cm per each 2.5 cm of rainfall. This amounted to a downward movement of approximately 60 cm during the Australian wet season. The practical implications of nitrate loss from the root zone due to leaching were discussed. Kelley (1964) presented a review of investigations of cation exchange and semiarid soils and discussed the practical requirements to be considered in irrigation.

An experiment by Miller, Biggar, and Nielsen (1965) demonstrated that chloride movement could be altered or controlled with the method of water application. They found a lower total of water was needed to leach the applied chloride to a given soil depth using intermittent 5 cm water applications than for 15 cm applications. Cassel (1971) investigated water and solute movement during a 3-month period for two water management regimes (evaporation and no evaporation). He found leaching of salts downward in the soil profile for all increments of water applied was more efficient for the covered (no evaporation) than for the bare (evaporation) plot.

Stone, Horton, and Olson (1973b) used a knowledge of soil water flux below the root zone and the rate of profile water storage change to estimate ET rates of a sorghum crop. The common methods of estimating ET have been by using lysimeters, microclimatological methods, or profile water depletion while neglecting deep profile soil water flux as discussed earlier.

Lysimeters are large containers of soil positioned in the field to approximate the soil and climatic conditions of the field environment. Discussions of lysimeter methodology, use, and problems are given by such authors as van Bavel and Reginato (1965), Hanks and Shawcroft (1965), Ritchie and Burnett (1968), and Rosenberg, Hart, and Brown (1968). Two papers which discuss ET rates obtained using lysimeters are by van Bavel (1961) and McGuinness and Bordne (1972).

Many formulas and methods have been proposed for using microclimatological data in estimating potential or actual evapotranspiration. Potential evapotranspiration is that which would occur with a given atmospheric demand from a wet surface, i.e., a water surface or a field recently watered where there is no restriction on the availability of water for evapotranspiration (Bartholic, Namken, and Wiegand, 1970). There have been numerous reviews of ET equations over the years, three of the more recent have been by Rosenberg et al. (1968), Bartholic et al. (1970), and McGuinness and Bordne (1972).

The energy balance of a crop surface can be given by

$$Rn + S + LE + A + PH + M = 0 \tag{6}$$

where Rn is net radiation, S is soil heat flux, LE is the energy consumed in evaporation (L is the latent heat of vaporization and E is the quantity of water evaporated), A is the sensible heat to the air, PH is the energy used in photosynthesis, and M represents other miscellaneous energy used. Net radiation is the overall difference between total incoming and total outgoing radiation (including both the shortwave and longwave components). The energy used in photosynthesis has usually been estimated at 1 to 2% of net radiation. Lemon (1960) estimated photosynthesis of corn to be approximately 5% of net radiation at midday and nearly 8% for the total daylight period. Because of the difficulty in obtaining field measurement of photosynthesis efficiency and because it is in general less than 5% of Rn, the photosynthesis (PH) term is generally omitted from the energy balance measurements. If the miscellaneous (M) term is also neglected, the energy balance equation becomes

$$Rn + S + LE + A = 0 \tag{7}$$

for a crop canopy. The sign convention used is that all energy fluxes to the crop canopy are positive and that all energy fluxes away from the crop canopy are negative.

The energy balance equation (7) can be solved utilizing the Bowen ratio (Bowen, 1926). The Bowen ratio (B) is defined as the ratio of sensible heat (A) transport to latent heat (LE) transport. For steady state conditions, the vertical flux of sensible heat may be expressed by

$$A = Cp\rho K_H(\partial T/\partial z) \tag{8}$$

where Cp is the specific heat of air at constant pressure, ρ is the density of air, K_H is the transfer coefficient for heat, T is the air temperature, and z is the height. The vertical flux of latent heat may be represented by

$$LE = [(M_w/M_a)/P][L\rho K_w(\partial e/\partial z)] \tag{9}$$

where M_w is the molecular weight of water, M_a is the molecular weight of air, P is the atmospheric pressure, L is the latent heat of vaporization, K_w is the transfer coefficient for water vapor, and e is the vapor pressure. Putting equations (8) and (9) in Bowen ratio form yields

$$B = PC_p\rho K_H(\partial T/\partial z)/\{(M_w/M_a)[L\rho K_w(\partial e/\partial z)]\} \tag{10}$$

with the terms defined earlier. In using the Bowen ratio it is generally assumed that $K_H = K_w$, a point discussed by Tanner (1960) and Brown and Rosenberg (1971). The bulk of the evidence available supports the validity of the assumption that $K_H = K_w$. The Bowen ratio equation utilizes the psychrometric constant which is given as

$$G = (C_pP)/(LM_w/M_a) \tag{11}$$

(Tanner, 1960). If the temperature and vapor pressure measurements are taken over the same interval, then equation (10) may be written in finite increment form

$$B = G\Delta T/\Delta e \tag{12}$$

where ΔT and Δe are changes in temperature and vapor pressure over the same vertical distance. Using the Bowen ratio, equation (7) becomes

$$LE = -(Rn + S)/(1 + B) \tag{13}$$

where LE is the evaporative flux or estimated evapotranspiration rate in a cropped area.

The Penman (1948) method for estimating potential evapotranspiration utilizes both energy balance and aerodynamic principles. The general form of the Penman equation is

$$E = (DH + 0.27E_a)/(D + 0.27) \tag{14}$$

where E is an estimate of evaporation loss from an open water surface in mm/day, D is the slope of the saturation vapor pressure curve for water at mean air temperature, H is an estimate of net radiation in evaporation equivalents of mm/day, and 0.27 is the psychrometric constant (mm Hg/F). The E_a term is found using the equation

$$E_a = 0.35(e_s - e_a)(1 + u/100) \tag{15}$$

where e_s and e_a are the saturated and actual vapor pressure of the air in mm Hg and u is the wind speed at a height of 2 m in miles/day.

Tanner and Pelton (1960) found Penman ET estimates from an alfalfa-brome stand were well correlated with, but lower than, those obtained with detailed energy balance measurements. They concluded the error to be primarily due to the Penman wind function term which was developed for open water surfaces and does not account for surface roughness in a cropped area. Rosenberg (1969) also found Penman ET estimates to be slightly less than lysimeter values. He did find the Penman estimates to be independent of windiness, a fact of importance in the Great Plains states.

Van Bavel (1966) built on Penman's earlier work and formulated an expression, containing no empirical constants or functions, for estimating potential evaporation. He used a combination of a surface energy balance equation and an approximate expression of water vapor and sensible heat transfer to obtain the equation. The van Bavel equation for potential evapotranspiration rates is given by

$$LE = -[(D/G)H + LB_v d_a]/[(D/G) + 1] \qquad (16)$$

where H is the sum of net radiation and soil heat flux, d_a is the vapor pressure deficit at elevation z_a, and B_v is a turbulent transfer coefficient for water vapor. The term B_v is defined by

$$B_v = [(\rho k^2 M_w/M_a)/P]\{u_a/[\ln(z_a/z_o)]^2\} \qquad (17)$$

where k is the von Karman constant, u_a is the wind speed at elevation z_a, z_a is the elevation above the soil surface, and z_o is the roughness parameter.

In the original work, van Bavel (1966) found acceptable hourly and daily agreement between measured and estimated evaporation from open water, wet soil, and well-watered alfalfa. McGuinness and Bordne (1972) working with alfalfa in Ohio found the van Bavel equation estimated lysimeter ET better than the Penman equation.

Rosenberg (1969) also found results using the van Bavel method agreed more closely with lysimeter ET than did results using the Penman method. The van Bavel method has been shown to be very sensitive to windiness (Skidmore, Jacobs, and Powers, 1969; Rosenberg, 1969).

The development and availability of the radiation thermometer has increased the desire to use canopy temperatures in estimation of ET rates and plant water stress. The relationship between canopy surface temperature and plant water stress was discussed by Horton, Namken, and Ritchie (1970). The surface temperatures can be determined locally in the field or remotely using aircraft (Bartholic et al., 1972). When using radiation thermometers, the emissivity of the test surface, long-wave sky radiation, and atmospheric attenuation must be considered if accurate results are to be obtained (Conaway and van Bavel, 1967a; Conaway and van Bavel, 1967b; Bartholic et al., 1972). Investigations by Fuchs and Tanner (1966) and Conaway and van Bavel (1967a) indicate that accuracies of ± 0.2 C may be achieved routinely if the three factors discussed above are taken into account.

Bartholic et al. (1970) discussed an energy balance-Bowen ratio type equation which uses surface temperature in estimating potential evaporation from a wet surface with infinite fetch (an expanse with similar roughness characteristics and moisture conditions). The crop canopy is assumed to be a wet surface with no water vapor pressure deficit. Therefore, the canopy vapor pressure is given by the saturation vapor pressure at the prevailing canopy temperature. Slatyer and Gardner (1965) discuss that even with leaf potentials of -50 bars, the relative vapor pressure is 96% at normal temperatures. The above assumption is then usually acceptable for experimental purposes. A further assumption is that the air near the surface is saturated and the air vapor pressure is approximated by the saturation vapor pressure at air temperature. Potential evaporation is expressed by the equation discussed by Bartholic et al. (1970)

$$E_p = -(Rn + S)/\{1 + G[(T_a - T_o)/(e_a' - e_o')]\} \quad (18)$$

where E_p is potential evaporation, T_a is air temperature at height a, T_o is surface temperature, e_a' is the saturated water vapor pressure at T_a, and e_o' is the saturated water vapor pressure at T_o.

Another equation using surface temperatures to estimate evapotranspiration was discussed by Brown and Rosenberg (1972). The equation is formed by placing the equation for sensible heat flux (8) into the surface energy balance equation (7). The temperature difference in equation (8) becomes surface temperature minus air temperature. The term (K_H/z) is replaced by h, where h is the transport coefficient for heat and water vapor and is sometimes termed the eddy conductivity. The resistance to transport in air (r_a) is given by 1/h. Equation (7) upon substitution becomes

$$LE = -(Rn + S) + [Cp\rho(T_o - T_a)/r_a] \quad (19)$$

where LE is the energy consumed in evaporation and T_a is air temperature at elevation z_a. The portion of the equation relating sensible heat flux and surface-to-air temperature difference $[C_p\rho(T_o - T_a)/r_a]$ is often referred to as Newton's Law of Cooling. From Szeicz, Endrodi, and Tajchman (1969) and Bartholic et al. (1970), $r_a = 1/h$ and

$$h = k^2u_a/\{\ln[(z_a - d)/z_o]\}^2 \tag{20}$$

where d is the zero plane displacement. Equation (20) assumes neutral stability (air temperature gradient to be constant with elevation). Under conditions of well-watered vegetation and when working near the crop surface, h as determined from equation (20) is believed to work satisfactorily (Bartholic et al., 1970).

Data collected using the van Bavel, Penman, and energy balance-Bowen ratio methods are quite common in the literature. The equations have been used over a wide expanse of climate and crop factors and have usually performed adequately. The methods proposed by Bartholic et al. (1970) and Brown and Rosenberg (1972) are virtually without supporting data. In view of the powerfulness of the surface temperature approach to estimate ET, these two methods should be evaluated against older more established methods. The work reported in this thesis was aimed in part at evaluating these two new and untested methods.

Most of the water lost by evapotranspiration is lost as evaporation from plants (transpiration). During each of two crop years, Ritchie and Burnett (1971) estimated that transpiration from grain sorghum contributed 80% of the total evapotranspiration amount. Transpiration from plants occurs mainly through the stomates of leaves, but small amounts of water vapor are lost from leaves by direct evaporation from the epidermal cells through the cuticle. Meyer, Anderson, and Bohning (1960) stated that 80 to 90% of the water vapor lost by plants is lost through stomatal transpiration. Outward diffusion of water vapor through the stomatal openings takes place when the vapor pressure in the intercellular spaces is greater than that in the atmosphere. Oxygen and carbon dioxide also enter or depart from a leaf principally through the stomates.

Stomates, or stomata, are minute pores which occur in the epidermis of plants. They are surrounded by two distinctive epidermal cells known as guard cells and occur primarily on the leaves. The degree of stomatal opening is dependent upon the turgor pressure difference between the guard cells and the surrounding epidermal cells. An increase in the turgor of the guard cells relative to that of the epidermal cells leads to a widening of the stomatal aperture, and vice versa (Meyer et al., 1960). Turgor pressure of the guard cells is affected by leaf water potential, temperature, light, and CO_2 concentration of the ambient air (Ketellaper, 1963). Slatyer (1967) stated that under most field conditions, leaf water potential and light are the primary factors governing stomatal movement. This agrees with data by Brown and Rosenberg (1970) that shows mean stomatal resistances to diffusion of water vapor and CO_2 in a field study to be independent of CO_2 concentration, air temperature, water vapor pressure, and wind speed.

It is well documented that stomatal opening is strongly regulated by illumination. Ehrler and van Bavel (1967) stated that stomatal aperture in well-watered crops is determined primarily by illumination. Generally, stomata are closed in the dark and open in the light, opening wider with progressively higher illumination until a saturation value is reached. Ehler and van Bavel (1968) estimated the saturation illuminance to be approximately 50 klux (0.6 ly/min). Drake, Raschke, and Salisbury (1970) in a growth chamber study found that leaf resistances to water vapor transfer decreased with increasing temperature due to increased stomatal apertures. They also found that at constant air temperature, leaf resistances were higher in dry than in moist air.

Leaf water deficit is due to an imbalance in the rates of transpiration and water absorption. It can be generated either by an increase in evaporative demand or by a lowering of water absorption (Ehrler and van Bavel, 1967). The lowering of water absorption is usually a result of limited soil water availability. The leaf water deficit reduces turgor pressure in the guard cells and causes stomatal closure which causes increased leaf resistance to evaporation and increased leaf temperature. That water stress in plants causes premature closure of stomata which increases leaf resistance to vapor transfer has been discussed by Kramer (1963), Ehrler and van Bavel (1967), and Szeicz et al. (1969). Szeicz and

Long (1969) found that at moderate rates of evaporation (0.2-0.3 cm/day), the surface resistance of a grass-clover crop was maintained at a minimum until the soil water potential in the top 25 cm layer decreased to between -3 and -4 bars. The surface resistance then increased almost linearly as soil water potential decreased further to about -12 bars. Brown and Rosenberg (1970) found mean daily stomatal resistance increasing as the soil water potential decreased from -0.35 to -0.52 bars. The linear increase in stomatal resistance found with decreasing soil water potential indicated that no threshold soil water potential existed below which the sugar beet stomatal resistances were independent of soil water supply. The results obtained by Brown and Rosenberg (1970) suggested that even under well-irrigated conditions, climatic stresses characteristic of the Great Plains environment could induce partial stomatal closure during afternoon hours on many days.

Another factor influencing leaf resistance to water vapor diffusion and CO_2 exchange is the leaf age. Szeicz et al. (1969) stated that stomata do not open wide in old leaves. Monteith, Szeicz, and Waggoner (1965) reported that resistance of barley increased as the crop matured, with the increase attributed to development and maturation of the crop.

This review has investigated the literature dealing with the evapotranspiration and water movement terms of the water conservation equation. In some instances, more papers discussed a pertinent topic than are listed. In attempting to keep the list within reasonable size, excellent articles may have been omitted. Building upon this review, a study was conducted: 1) to further investigate the significance of the flux term and 2) to investigate the actions of canopy temperature and the possibility of using canopy temperature in determining water use by crops.

MATERIALS AND METHODS

The work reported in this thesis was conducted on the James Valley Agricultural Research and Extension Center located 9.65 km east of Redfield, S. D. The soil at the experimental site has been classified as Great Bend silt loam, a Udic-Hapoboroll fine silty mixed soil occurring on level positions in the southern part of the Glacial Lake Dakota Plain (Westin et al., 1954). A detailed description of the soil profile at the test site is given in Table 1.

The test area was 145 m east-west by 305 m north-south. Nitrogen and phosphorus fertilizers were applied and the field planted to grain sorghum (Sorghum bicolor (L.) Moench.) on June 12 in rows spaced 54 cm apart. Recorded dates of importance in the sorghum development were: 1) June 17, emergence; 2) July 12, sprayed for greenbugs; 3) August 6, boot stage; 4) August 16, half bloom; 5) August 27, soft dough; and 6) November 16, grain harvest. In July the field was sectioned into a nonirrigated area (northern 1/3) and an irrigated area (southern 2/3). Research equipment to be discussed later was then positioned in each area. Rainfall and irrigation amounts received at the test site are given in Fig. 1. The two irrigations (12 cm on August 7 and 8 cm on August 19) were applied using furrow irrigation. Plants were collected on August 23 for determination of size, population, and leaf area index (LAI). Both the irrigated and nonirrigated areas were found to have a plant population of approximately 185,000 plants/ha. Height of

Table 1. Detailed profile description of the Great Bend silt loam soil.

Location: James Valley Research and Extension Center, Redfield, South Dakota.

Described by: Dr. C. J. Frazee, Plant Science Department, South Dakota State University.

Parent Material: Laminated Lacustrine Silt.

Horizon	Depth (cm)	Description
Ap	0- 23	Very dark gray (10YR3/1) moist; silt loam; weak fine and moderate granular structure; very friable when moist; abrupt smooth boundary; noncalcareous.
B21	23- 37	Dark brown (10YR3/3) moist; silt loam; weak medium prismatic structure parting to weak medium subangular blocky structure; very friable when moist; clear smooth boundary; noncalcareous.
B22	37- 48	Olive brown (2.5Y5/4) moist; silt loam; weak coarse prismatic structure; very friable when moist; clear smooth boundary; noncalcareous.
C1ca	48- 85	Olive brown (2.5Y5/4) moist; silt loam; massive; friable when moist; clear smooth boundary; highly calcareous.
C2	85-150	Olive brown (2.5Y4/4) moist with 10YR5/6 iron stains between plates; laminated silt loam; medium moderate plates; friable when moist; highly calcareous.

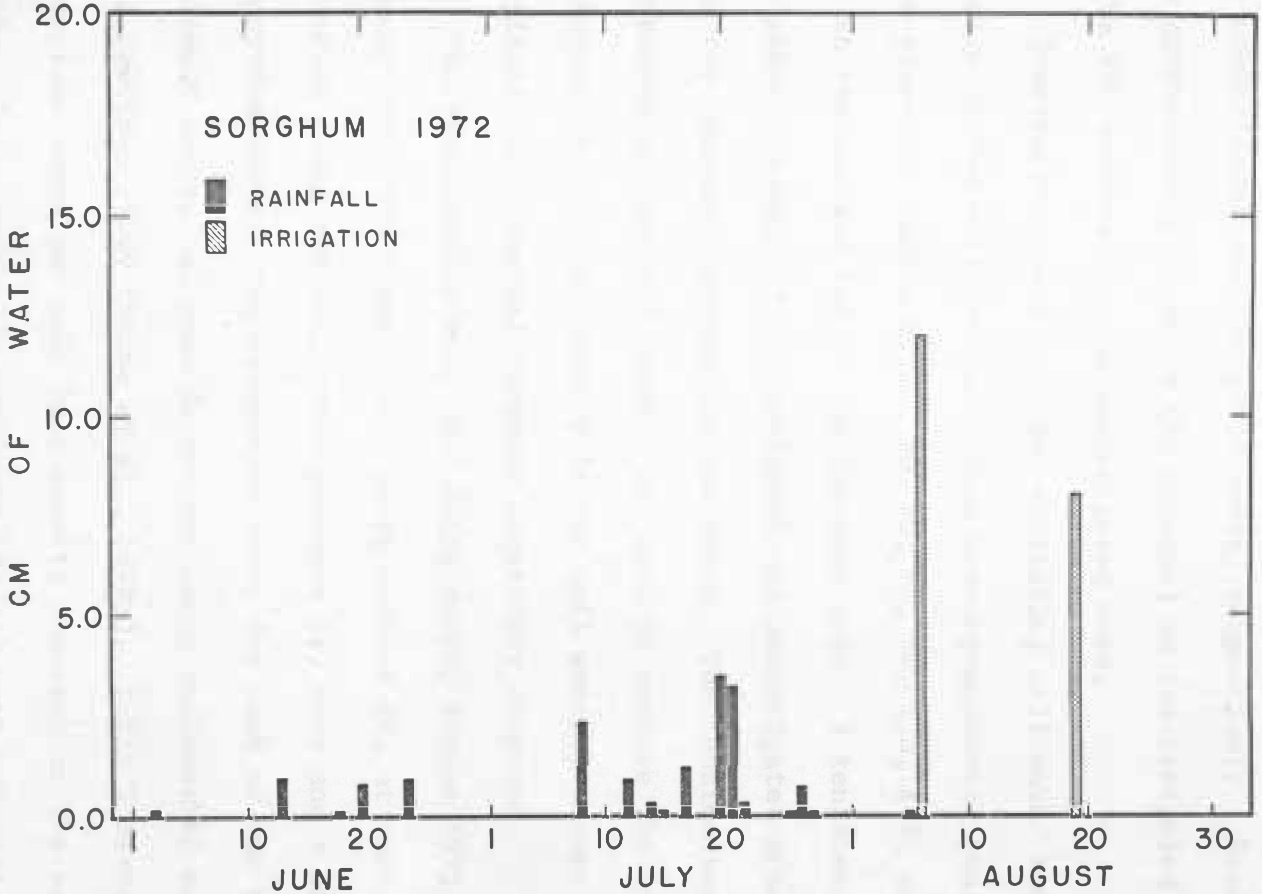

Fig. 1. Rainfall and irrigation amounts received at the test site during study.

leaf canopy was approximately 80 cm in the nonirrigated area and 85 cm in the irrigated area. The LAI was found to be 2.8 and 3.2 for the nonirrigated and irrigated areas, respectively. Grain yield was approximately 71 hl/ha (82 bu/acre) in the irrigated area and 65 hl/ha (75 bu/acre) in the nonirrigated area.

Tensiometers were used for estimating soil water movement and storage in the soil profile. Four mercury-manometer tensiometers were placed at depths of 15, 30, 50, 70, 90, 110, 130, and 150 cm, two in the row and two in the interrow area. A tensiometer battery was placed in each of the irrigated and nonirrigated areas 10 m from the boundary between the two areas. The tensiometers were referenced to the soil surface and used to measure the hydraulic potential, $\Phi = \psi + z$, where ψ is the soil water pressure and z the gravitational potential directed negatively downward.

The tensiometers were read daily during August 1972, normally between 0700-0800 hours. Soil water content (θ) at each depth was estimated using the soil water pressure (ψ) data and a soil water desorption curve. The desorption curve for each of the tensiometer placement depths had been determined using undisturbed soil cores in a previous study (Stone et al., 1973a). Table 2 lists the desorption curve and soil bulk density for each of the various depths. Daily hydraulic gradients ($\partial\Phi/\partial z$) were calculated using the hydraulic potential readings (Φ) and a knowledge of tensiometer placement depth (z). The hydraulic conductivity vs. water content relationship for the various soil depth intervals is given in Fig. 2.

Table 2. Values of soil water content versus soil water pressure and values of soil bulk density for Great Bend silt loam.

Soil Water Pressure (cm of water)	Depth (cm)								
	0	15	30	50	70	90	110	130	150
	Soil Water Content (cm^3/cm^3)								
- 5	0.433	0.443	0.442	0.436	0.468	0.497	0.521	0.515	0.525
- 20	0.381	0.393	0.410	0.412	0.456	0.490	0.507	0.506	0.516
- 40	0.354	0.366	0.386	0.395	0.445	0.483	0.499	0.500	0.511
- 60	0.340	0.352	0.371	0.384	0.438	0.477	0.494	0.496	0.507
- 90	0.328	0.340	0.355	0.372	0.429	0.470	0.488	0.492	0.503
-130	0.318	0.330	0.341	0.361	0.419	0.462	0.483	0.488	0.499
-180	0.311	0.323	0.330	0.350	0.409	0.455	0.478	0.485	0.495
-240	0.304	0.315	0.319	0.339	0.399	0.447	0.474	0.481	0.492
-310	0.298	0.309	0.311	0.330	0.390	0.439	0.469	0.478	0.488
-400	0.292	0.302	0.302	0.319	0.379	0.431	0.463	0.473	0.483
-800	0.273	0.286	0.237	0.292	0.346	0.414	0.452	0.465	0.475
	Soil Bulk Density (g/cm^3)								
	1.15	1.17	1.19	1.16	1.24	1.22	1.18	1.23	1.23

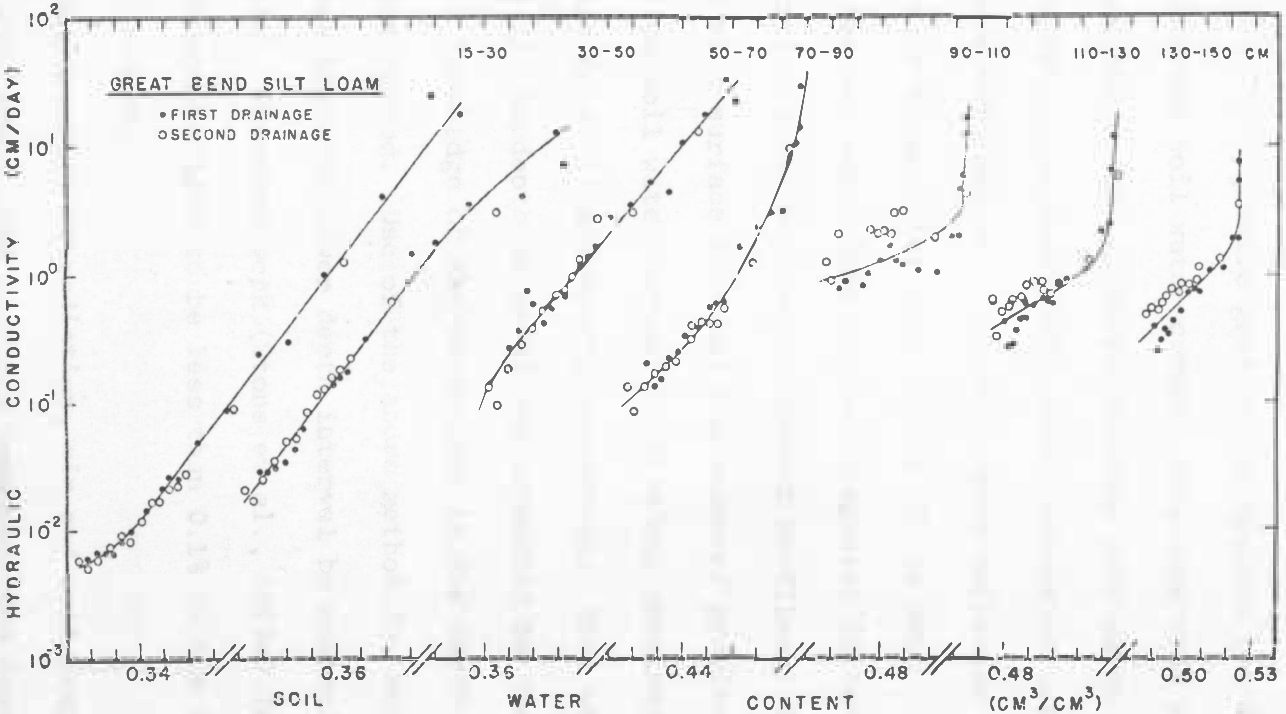

Fig. 2. Hydraulic conductivity versus soil water content for Great Bend silt loam measured at seven soil depth intervals.

These relationships were determined in a previous study and are reported along with the methodology by Stone, Olson, and Horton (1973c). The hydraulic gradient values and the hydraulic conductivity versus soil water content data were used with Darcy's equation (5) to calculate the average soil water flux.

Daily evapotranspiration rates estimated using tensiometer data were obtained as total soil water depletion in the 0 to 150 cm profile minus water flux at the 150 cm depth. Soil water depletion was determined as the integrated difference between consecutive daily soil water content profiles. The water content of the soil surface (0-4 cm) was measured gravimetrically. The 15 to 150 cm soil water content profile was obtained using soil water pressure data (ψ) and desorption curves. Soil water flux in the 130 to 150 cm depth interval was corrected to the 150 cm depth using a knowledge of the water loss in the depth interval during the time period. Use of the above method for estimating ET rates requires that the lower depth interval be essentially free of root activity. Previous work (Stone et al., 1973a) indicated grain sorghum root weight to be less than 0.1% in the 130 to 150 cm depth interval.

Measurements of radiation, air and soil temperature, soil heat flux, wind speed, and humidity were recorded during the study. Instruments used for their measurement were positioned in the respective study area 30 to 50 m from the irrigated-nonirrigated boundary. A mobile field laboratory was located at the boundary and housed recording equipment. All measurements were recorded automatically except humidity. Humidity measurements were made using a portable nonrecording instrument to be discussed later.

Incoming shortwave or global radiation (total of direct solar and sky radiation) was measured with a Kipp Zonen Model G18 solarimeter. The instrument was located approximately 2.5 m above the soil surface in an area allowing an unobstructed field of view and measured incoming radiation in the 0.3 to 3.5 μm wavelength range. The Kipp solarimeter was calibrated and had a determined response of 8.73 mv min/ly. Incoming shortwave radiation at 10 cm elevation within the crop canopy was measured on selected dates using a line pyranometer. The instrument had a determined response of 11.36 mv min/ly. Net radiation measurements above the crop canopy were made using Fritschen miniature net radiometers (Fritschen, 1965). A net radiometer was located at an elevation of approximately 2.5 m in both the irrigated and nonirrigated area. The instrument measures total incoming radiation minus total outgoing radiation in the 0.3 to 50 μm wavelength range. The radiometer outputs were 2.88 and 2.91 mv min/ly for the radiometers placed in the irrigated and nonirrigated areas, respectively.

Air and soil temperatures were determined using 24 gauge copper-constantan thermocouples constructed using welded junctions. An air tower constructed of polyvinyl chloride (PVC) with insulated sampling ports at elevations of 20, 40, 80, 160, 240, and 320 cm was positioned in each of the two study areas. A thermocouple was mounted in each port and aspiration was provided to ensure representative sampling. Soil temperatures were taken at depths of 2.5, 5, 10, and 30 cm in both the irrigated and nonirrigated sorghum areas.

Soil heat flux was measured during the study in both the irrigated and nonirrigated areas. Two rectangular heat flux plates were placed 2 m apart in the interrow area at a depth of 5 cm in each area. The values from the two plates were averaged to yield the soil heat flux for an area.

Radiation instruments, thermocouples, and soil heat flux plates were all recorded automatically at 10-minute intervals using a Howell H2812 data logging system. Thirty channels were recorded, requiring about 90 seconds total time. The system consists of a digital voltmeter, scanner, punch converter, and paper-tape punch. The system can accept sensor outputs in the range of -10 to 30 mv. A Joseph Kaye thermocouple reference system, Model 2700, had been added to the data logger system and was used to reference up to 24 thermocouples. The reference system operates in the ambient air temperature range of -30 to 55 C with a sensitivity of 0.5 C and a reference temperature of 65.6 C. The paper tape output was converted to computer cards at the South Dakota State University Computer Center. The center has an IBM 360 computer which was used in processing and analysis of data. A weighted arithmetic mean of all the 10-minute readings within an hour was determined where the initial and final 10-minute readings were weighted 1/2 as heavily as the 10-minute readings during the hour. The weighted arithmetic means for an hour were then used in data analysis.

Canopy temperature measurements were obtained using a Barnes Infrared Thermometer, Model IT-3, with a 3-degree field of view. The instrument was positioned 3 m above the soil surface on a trolley that moved on an overhead track 7 m in length. The trolley moved back and forth on the track driven by a reversible electric motor and bicycle chain. The complete cycle required 27.5 min., or the trolley moved at a speed of 0.51 m/min. The instrument was shaded from incoming shortwave radiation using styrofoam. This was done to decrease chances of error caused by instrument temperature increase as discussed by Jackson and Idso (1969).

The infrared thermometer was calibrated using an aluminum plate coated with Parsons black paint and containing two embedded thermocouples. The plate was positioned 1 m above the soil surface and in the thermometer scan line. Plate temperature was recorded every 10 minutes using the Howell H2812 data logger. Voltage output from the Barnes was recorded continuously during a scan cycle using a strip chart recorder. The black plate was scanned 4 or 5 times each hour during the course of the cycles. Data were reduced to yield a mean hourly temperature of the black plate and mean hourly mv response from the instrument caused by scanning the black plate. A simple linear regression equation was then determined and used to estimate surface temperature by the instrument mv response. The linear regression equation was

$$\text{Degree C} = 90.54 - 2.08 \text{ mv} \qquad (21)$$

with the number of observations being 205, standard error of the estimate being 2.35, and a r^2 value of 0.96. Due to instrument failure, the canopy temperature estimates on August 17 were obtained using a borrowed Barnes Model IT-3. It yielded a linear regression equation of

$$\text{Degree C} = 85.22 - 1.75 \text{ mv} \qquad (22)$$

with the number of observations being 31, standard error of the estimate being 1.16, and a r^2 value of 0.99.

As discussed in the literature review, there are three factors which need to be addressed when using field radiation thermometry. The following discussion considers the steps taken to minimize these error-causing factors. Literature indicates that the emissivity of most crops is near 0.98 (Fuchs and Tanner, 1966; Bartholic et al., 1972). Buettner and Kern (1965) reported the emissivity of an aluminum plate painted with Parson's black to be 0.988. Therefore, the emissivity difference between the calibrator plate and the crop canopy should have been 0.01 or less. This is consistent with results reported by Carlson (1972). Therefore, in this thesis work emissivity differences were assumed to be small and not corrected for. Because the instrument was field calibrated over a long span of time, the error introduced by longwave sky radiation (Conaway and van Bavel, 1967a) would be minimized. This is so because the instrument was reading the sky radiation during the black plate readings; therefore, this extra radiation was accounted for in the instrument calibration. Atmospheric attenuation in the instrument range (8 to 14 μm) is very small and at low altitudes on dry days can be neglected without introducing serious error (Bartholic et al., 1972).

Wind measurements were taken at two locations 1 m above the crop canopy using Belfort 3-cup anemometers. The anemometers register by driving electrical contacts which close at 1.609 km (1 mile) wind travel intervals. Wind data were recorded continuously on an event recorder using heat sensitive chart paper. The data were processed and are reported as the mean hourly wind speed obtained from the two anemometers.

Humidity data were obtained using a portable hand-held Atkins thermistor psychrometer. The instrument is a resistance thermometer using two separate semiconductor sensors (thermistors) as the temperature sensors. The wet bulb and dry bulb temperatures were obtained five or six times during the day at 80 cm (canopy elevation) and 180 cm. The instrument dial could be read to the nearest 0.3 C. Vapor pressures were calculated using the wet and dry bulb temperatures and then plotted. An hourly estimate of actual and saturated vapor pressure was then obtained from the plot for both the irrigated and nonirrigated areas.

Leaf diffusion resistance (LDR) measurements were made using a diffusion porometer discussed by van Bavel, Nakayama, and Ehrler (1965). The instrument employs a cup containing a LiCl sensor which responds to water vapor by causing a change in electrical resistance in an AC bridge circuit. The rate of change in resistance was timed using a stop watch and used to indicate the leaf resistance to vapor diffusion. The greater the stomatal closure, the more time required for vapor transfer from leaf to sensor. LDR measurements were taken on selected dates in both the irrigated and nonirrigated study areas. Measurements were taken between 1430 and 1630 hours Central Daylight Savings Time (CDT) on six randomly selected uppermost fully developed leaves in each area. The cup was positioned on the upper leaf surface and the time required for resistance change measured. The time, in seconds, for the humidity to increase the fixed amount was corrected for the temperature dependent factors of instrument sensitivity and molecular diffusivity of water vapor in air. The LDR values reported in this thesis are the mean corrected values for the six leaves in each area.

Five equations for estimating actual or potential evapotranspiration were given in their original form in the literature review. After the constants were estimated for the conditions of this study, the equations were each put into a working form. Some of the original symbols were changed to conform with identical terms in other equations.

Estimated actual evapotranspiration by energy balance-Bowen ratio requires determination of the psychrometric constant (G). Using equation (11) and the values listed in Table 3, G is

Table 3. Values of constants estimated for the conditions of the 1972 study and used in ET predictive equations.

Symbol	Description	Value
C_p	Specific heat of air at constant pressure	0.24 cal/gC
ρ	Density of air	1.15×10^{-3} g/cm^3
M_w	Molecular weight of water	18.0 g/mole
M_a	Molecular weight of air	28.9 g/mole
P	Atmospheric pressure	980 mb
L	Latent heat of vaporization	580 cal/g
k	von Karman constant	0.4 (dimensionless)
z_a	Instrument elevation above the soil surface	180 cm
z_o	Roughness length	8 cm
d	Zero plane displacement	20 cm
G	Psychrometric constant	0.65 mb/C

calculated to be 0.65 mb/C. The working formula for ET by the energy budget-Bowen ratio method becomes

$$ETEB = -(Rn + S)/[1 + .65(T_{180} - T_{80})/(e_{a180} - e_{a80})] \quad (23)$$

where ETEB is estimated ET in ly/min, Rn is mean net radiation in ly/min during the hour, S is the mean soil heat flux in ly/min during the hour, T_{180} is the mean air temperature during the hour at 180 cm in C, T_{80} is the mean air temperature during the hour at 80 cm in C, e_{a180} is the actual vapor pressure during the hour at 180 cm in mb, and e_{a80} is the actual vapor pressure at 80 cm during the hour in mb. Temperatures were measured using the thermocouple air towers, and vapor pressures were estimated using the Atkins psychrometer.

The conversion of the Penman equation (14) to units used in this study was similar to that done by Hanks et al. (1971). The working formula for estimating potential ET by the Penman method becomes

$$ETPN = -[(D/G)(Rn+S)+.011(1+.537u_{180})(e_{s180}-e_{a180})]/[(D/G)+1] \quad (24)$$

where ETPN is estimated potential ET in ly/min, D/G is found using the mean air temperature and a published table (van Bavel, 1966), u_{180} is mean wind speed during the hour in m/sec measured at z_a, and e_{s180} is saturated vapor pressure at z_a in mb determined using the Atkins psychrometer.

The working form of the van Bavel equation (16) is

$$ETVB = -[(D/G)(Rn+S)+(.045u_{180})(e_{s180}-e_{a180})]/[(D/G)+1] \quad (25)$$

where ETVB is an estimate of potential evapotranspiration in ly/min. The value of z_a in equation (17) was adjusted by using the zero plane displacement value. The term in (17) then became $\ln[(z_a-d)/z_o]$. The actual values of z_o and d shown in Table 3 were not measured due to lack of wind profile data necessary for their calculation. They were estimated for crop conditions of the study using published information (Lemon, 1960; Rose, 1966; Szeicz et al., 1969; Bartholic et al., 1970).

Two equations using surface temperatures to estimate evapotranspiration were used in this study. Surface temperatures used were an hourly estimate of canopy temperature obtained using the Barnes Infrared Thermometer. The Bartholic equation (18) in the working form is

$$ETBA = -(Rn+S)/[1+.65(T_{180}-T_{can})/(e'_{180}-e'_{can})] \tag{26}$$

where ETBA is potential evapotranspiration in ly/min, T_{can} is mean hourly canopy temperature in C, e'_{180} is the saturated vapor pressure at T_{180} in mb, and e'_{can} is the saturated vapor pressure at T_{can} in mb. Saturated vapor pressures were found using the published saturation vapor pressure over water versus temperature relationship (List, 1958). The working form of the Brown equation (19) is

$$ETBR = -[Rn+S-.029u_{180}(T_{can}-T_{180})] \tag{27}$$

where ETBR is estimated evapotranspiration in ly/min.

All statistical analyses reported in this thesis were conducted using Steel and Torrie (1960) and Spiegel (1961) as references.

RESULTS AND DISCUSSION

Soil water pressure (ψ) was determined daily at eight tensiometer depths during the study. The variation of soil water pressure with time for each depth is shown in Fig. 3 and 4. Figure 3 shows data obtained in nonirrigated sorghum and Fig. 4 was obtained for irrigated sorghum. Standard deviation (SD) of the mean for each depth was calculated on August 4, 10, 16, 22, and 28 in the non-irrigated plot and on August 10, 16, 22, and 28 in the irrigated plot. The mean value ± SD is shown where SD was greater than 2.0 cm of water. The SD values are usually greater when soil water pressures are decreasing rapidly with time.

Soil water pressures in the nonirrigated plot at depths of 15 and 30 cm decreased to approximately -800 cm of water (Fig. 3). The change in soil water pressure with respect to time decreased drastically after reaching the -750 cm level. Perrier and Evans (1961) stated that mercury-manometer tensiometers could be used to approximately -850 cm of water with reliability. The tensiometer readings for the 15 cm depth are approaching the limit for reliability and their values could be considered suspect after approximately August 10. The differential water capacity ($-d\theta/d\psi$) decreases (absolute value) as the soil water pressure decreases. As the soil dries, a given error in soil water pressure estimates would be accompanied by progressively smaller errors in soil water content estimates. Due to this fact, possible errors in the soil water

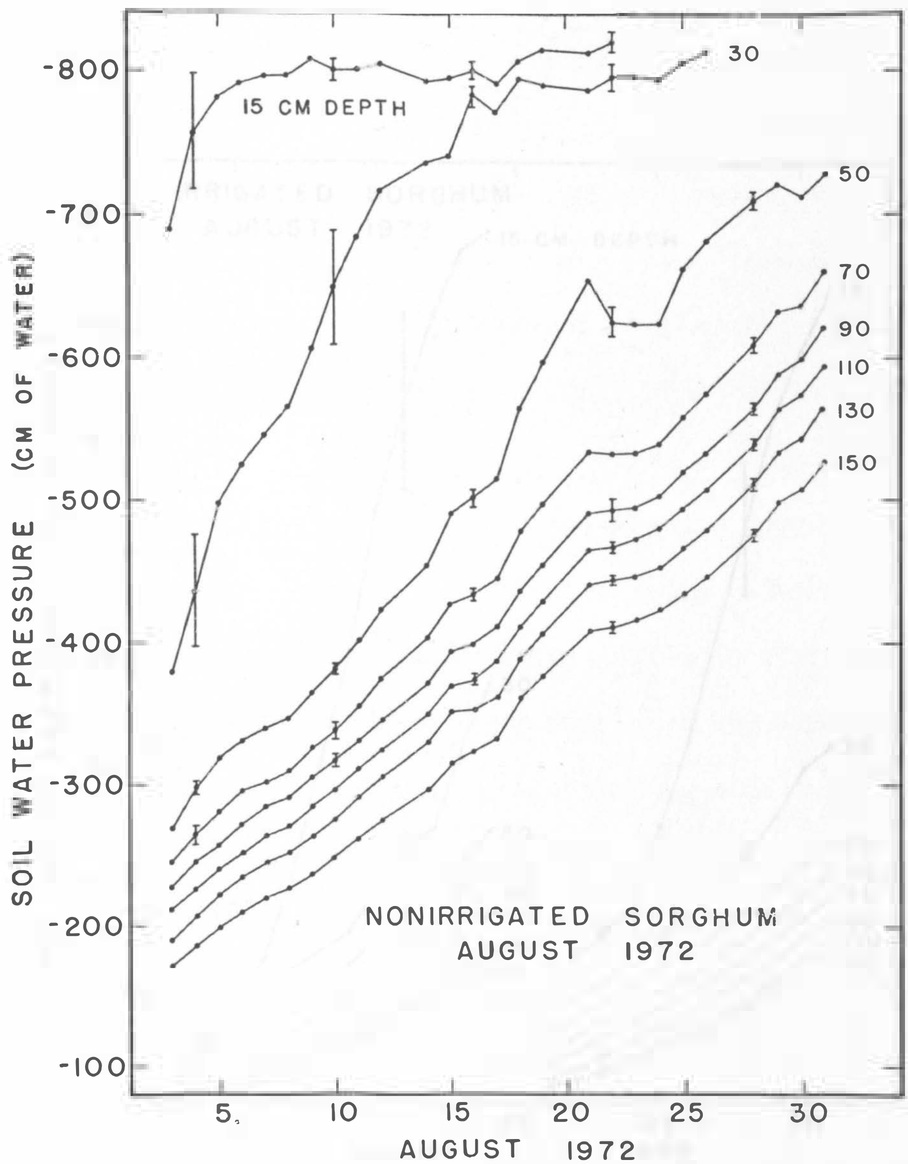

Fig. 3. Soil water pressure versus date for the eight tensiometer placement depths in nonirrigated sorghum. Each datum point represents a mean of four tensiometer readings. Standard deviation (SD) of the mean for each depth was calculated on August 4, 10, 16, 22, and 28. The mean value ± SD is shown where SD is greater than 2.0 cm water.

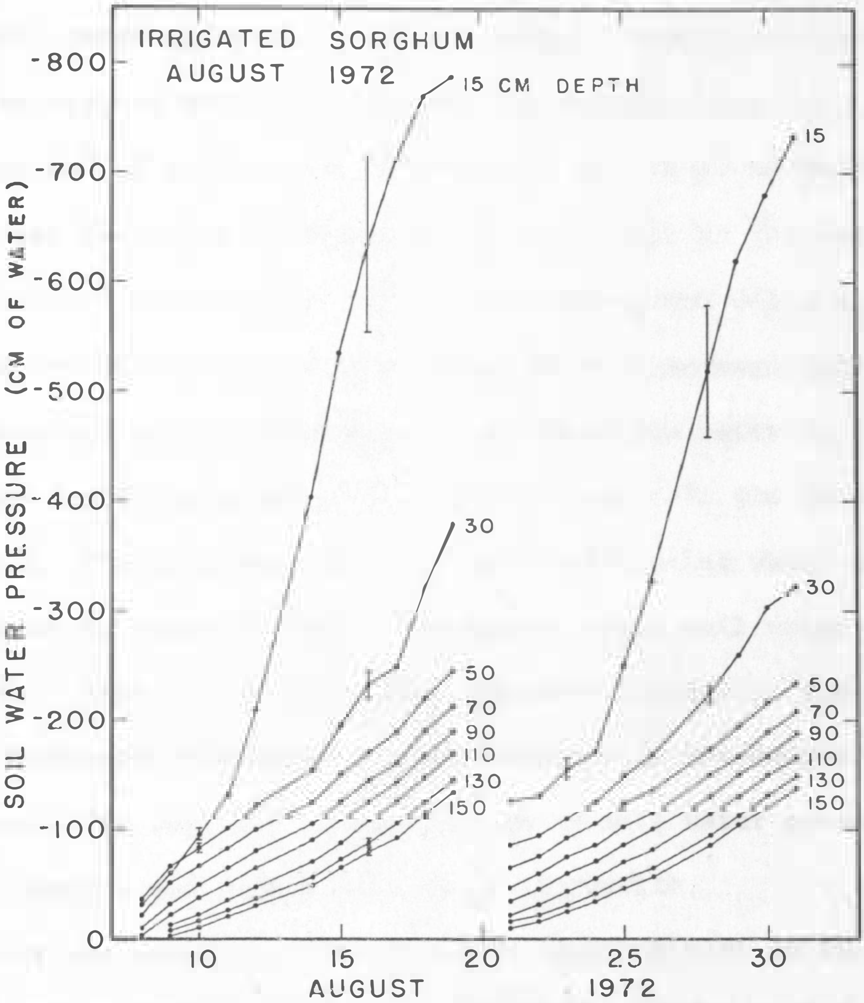

Fig. 4. Soil water pressure versus date for the eight tensiometer placement depths in irrigated sorghum. Each datum point represents a mean of four tensiometer readings. Standard deviation (SD) of the mean for each depth was calculated on August 10, 16, 22, and 28. The mean value ± SD is shown where SD is greater than 2.0 cm water.

pressure region of -800 cm of water would have little effect on water content errors, and even less effect when considering the entire 0-150 cm soil profile. Van Bavel, Stirk, and Brust (1968b) determined water contents of sorghum areas following irrigation using the neutron moderation method. They found that 0.31 cm^3 of water per cm^3 of soil volume was depleted at the 10 cm depth during the initial 15.5 days following irrigation. During the next 14 days, 0.02 cm^3 of water per cm^3 of soil volume was depleted. They observed depletions at the 20 cm depth of similar magnitudes as those observed at the 10 cm depth. As depletion rates in the shallower depths decreased, the depletion rates in the deeper depths increased. The patterns that were determined using water contents are similar to those in Fig. 3 determined using soil water pressures. That is, as soil water pressure changes in the shallower depths decreased, the water pressure changes in the deeper depths increased. The depth of maximum change in soil water pressure progressively moved deeper into the soil profile.

Water was applied to the irrigated sorghum plot on August 7 (12 cm) and on August 19 (8 cm). During the 12-day period following each irrigation, the pattern of soil water pressure change was similar (Fig. 4). The soil water pressure at the 15 cm depth decreased to approximately -750 cm of water during the 12 days. As drying at the 15 cm depth occurred, the soil water pressure decreased at an increasing rate at the 30 cm depth. The rate of soil water pressure change at depths of 50 cm and deeper was relatively constant with time. The water contents (θ) of the eight tensiometer depths were estimated using soil water pressure data from Fig. 3 and 4 and the desorption curves given in Table 2.

Average hydraulic gradients within a time period were determined using tensiometer data at each end of the time period and are presented versus date for nonirrigated and irrigated sorghum in Fig. 5 and 6, respectively. Average hydraulic gradients for four of the seven soil depth intervals are presented to avoid congestion. The hydraulic gradients ($\partial\Phi/\partial z$) were determined using the hydraulic potential readings (Φ) and a knowledge of tensiometer placement depth (z). Negative values of hydraulic gradient indicate upward water movement.

Hydraulic gradients in the nonirrigated sorghum (Fig. 5) were upward in direction for all but one measurement. The upward gradient in the 15-30 cm layer decreased (absolute value) with time during the study. The gradient in the 130-150 cm soil layer leveled off at approximately -0.6 cm/cm during the final three weeks of the study. Water was being supplied to the root zone from below the 150 cm depth and evapotranspiration was greater than water depletion in the 0-150 cm soil profile would indicate. Upward movement of water soluble salts would be expected to have occurred throughout the 0-150 cm soil profile during the study. The magnitude of the upward salt movement would be dependent upon the concentration of salts present, the solubility of the chemicals, the resistance of the soil to chemical movement, and the magnitude of the soil water flux.

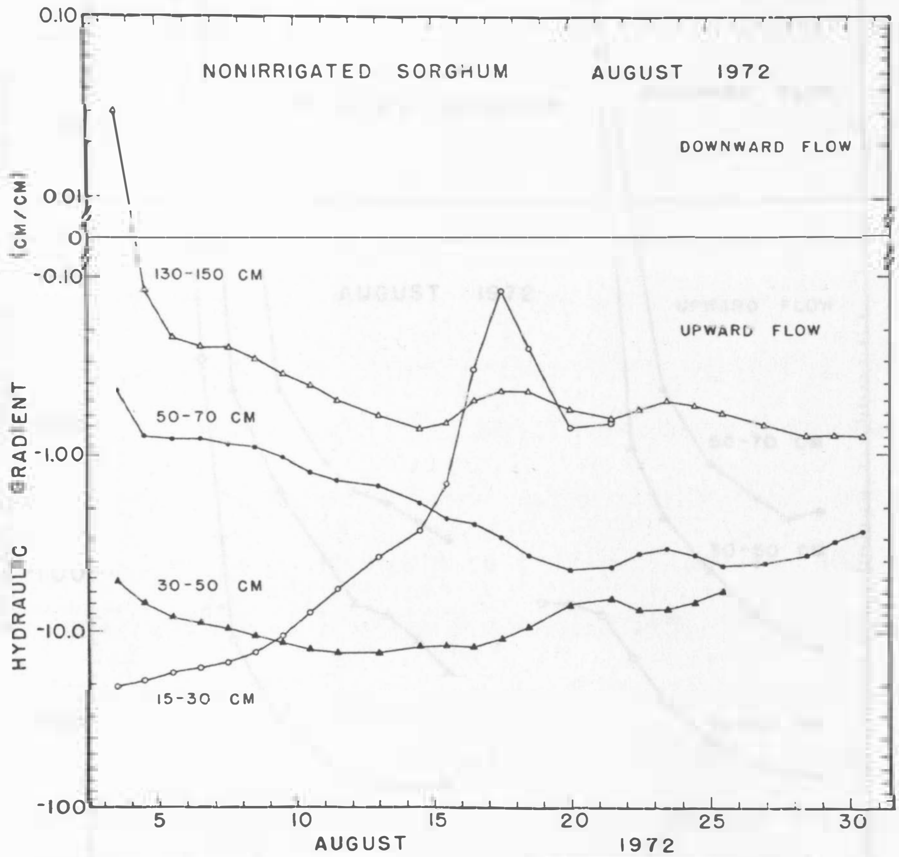

Fig. 5. Hydraulic gradient versus date for four depth intervals in nonirrigated sorghum. Negative values indicate upward water movement.

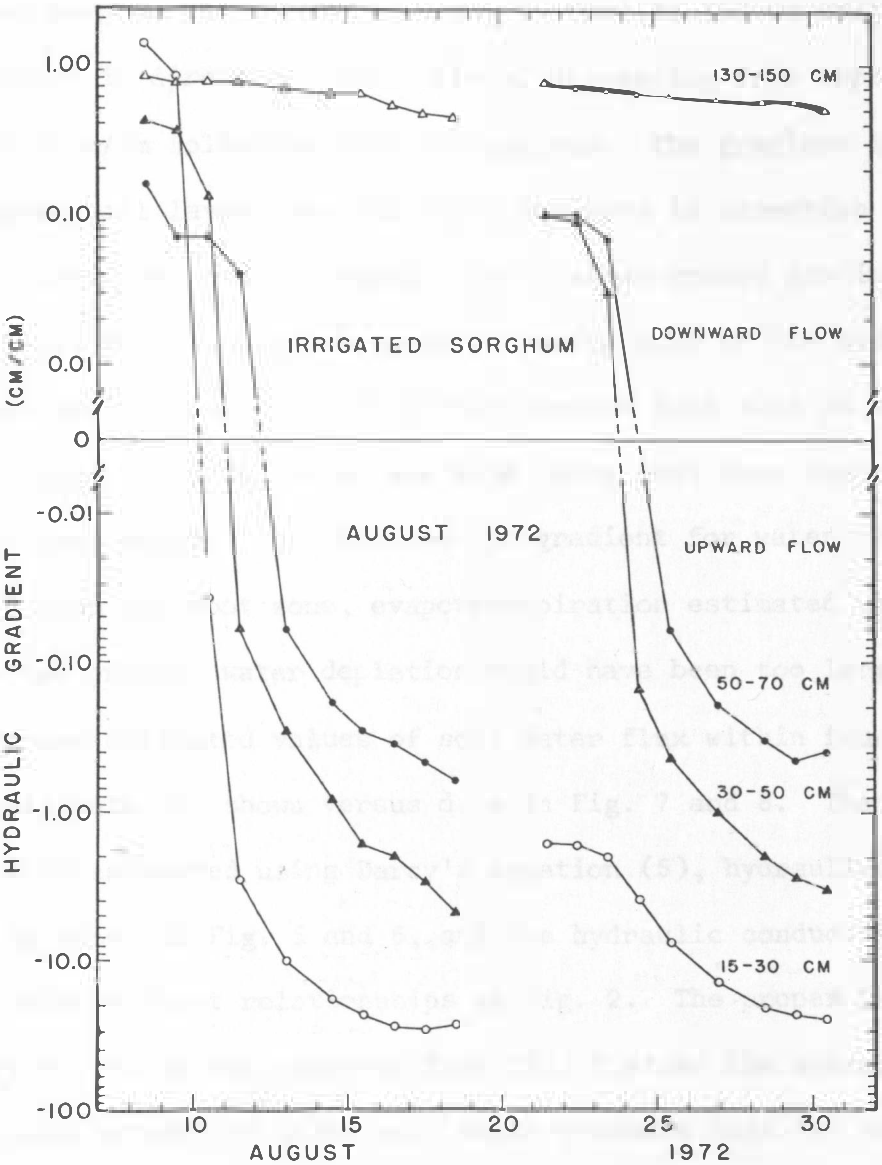

Fig. 6. Hydraulic gradient versus date for four depth intervals in irrigated sorghum. Negative values indicate upward water movement.

The hydraulic gradients shown in Fig. 6 were calculated using irrigated sorghum data. The gradient in the 130-150 cm soil layer was downward in direction at all times, decreasing from approximately 0.8 to 0.5 cm/cm following both irrigations. The gradient in the three upper soil layers was initially downward in direction and later reversed and became upward. The maximum upward gradient was in the 15-30 cm soil depth interval. During much of the study, water was moving from the bulk of the sorghum root zone in both vertical directions and water was also being lost from the profile by plant root extraction. Because the gradient for water flow was downward from the root zone, evapotranspiration estimated using uncorrected profile water depletion would have been too large.

Average estimated values of soil water flux within four soil depth intervals are shown versus date in Fig. 7 and 8. The flux values were estimated using Darcy's equation (5), hydraulic gradient values as shown in Fig. 5 and 6, and the hydraulic conductivity versus water content relationships of Fig. 2. The proper hydraulic conductivity value was selected from Fig. 2 after the average water content was determined using soil water pressure data (ψ) and Table 2. Negative values of soil water flux indicate upward water movement.

Figure 7 presents the estimated values of soil water flux for four soil depth intervals in the nonirrigated sorghum area. Upward flux in the 15-30 cm layer decreased (absolute value) to near zero on August 17. This was due to a decrease in magnitude of the upward

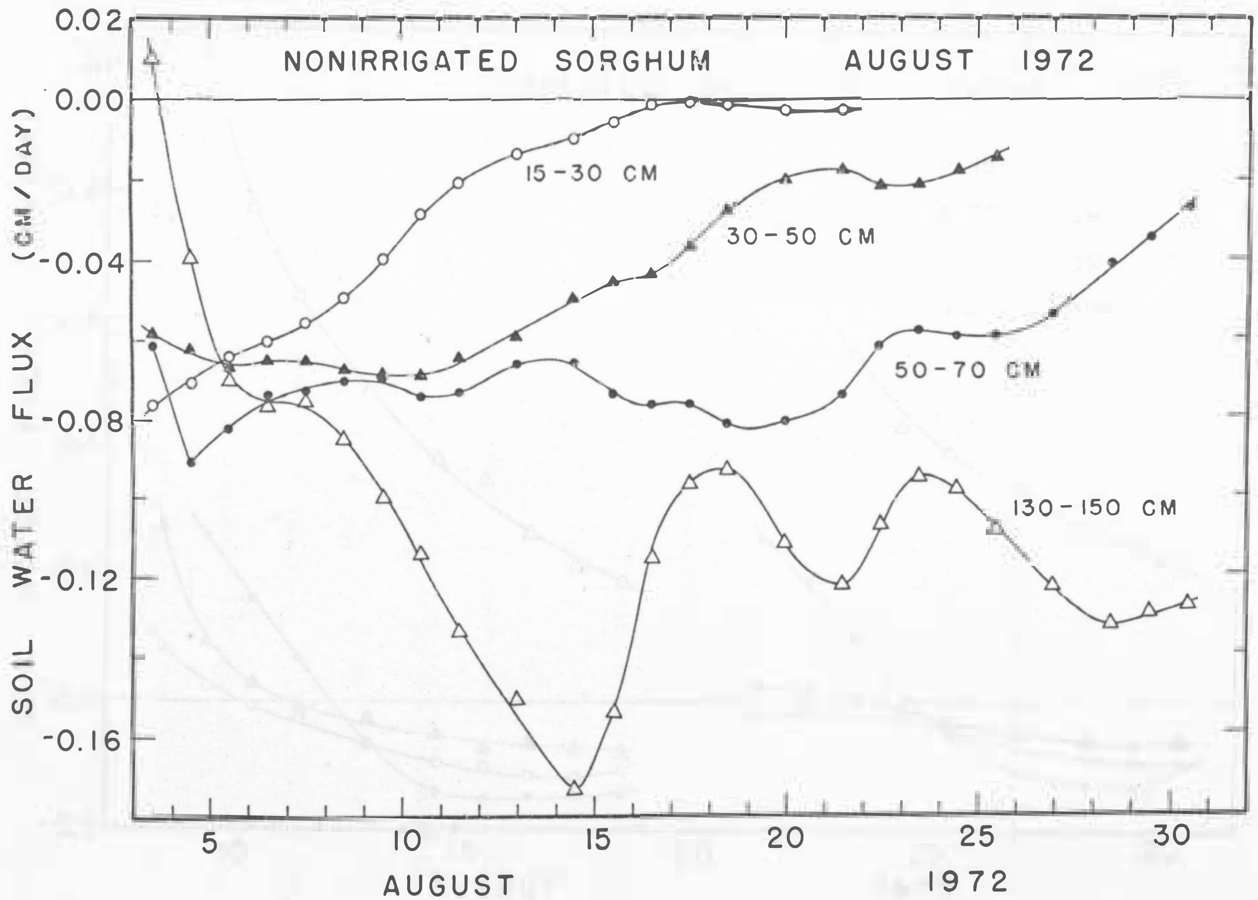

Fig. 7. Soil water flux versus date for four soil depth intervals in nonirrigated sorghum. Negative values indicate upward water movement.

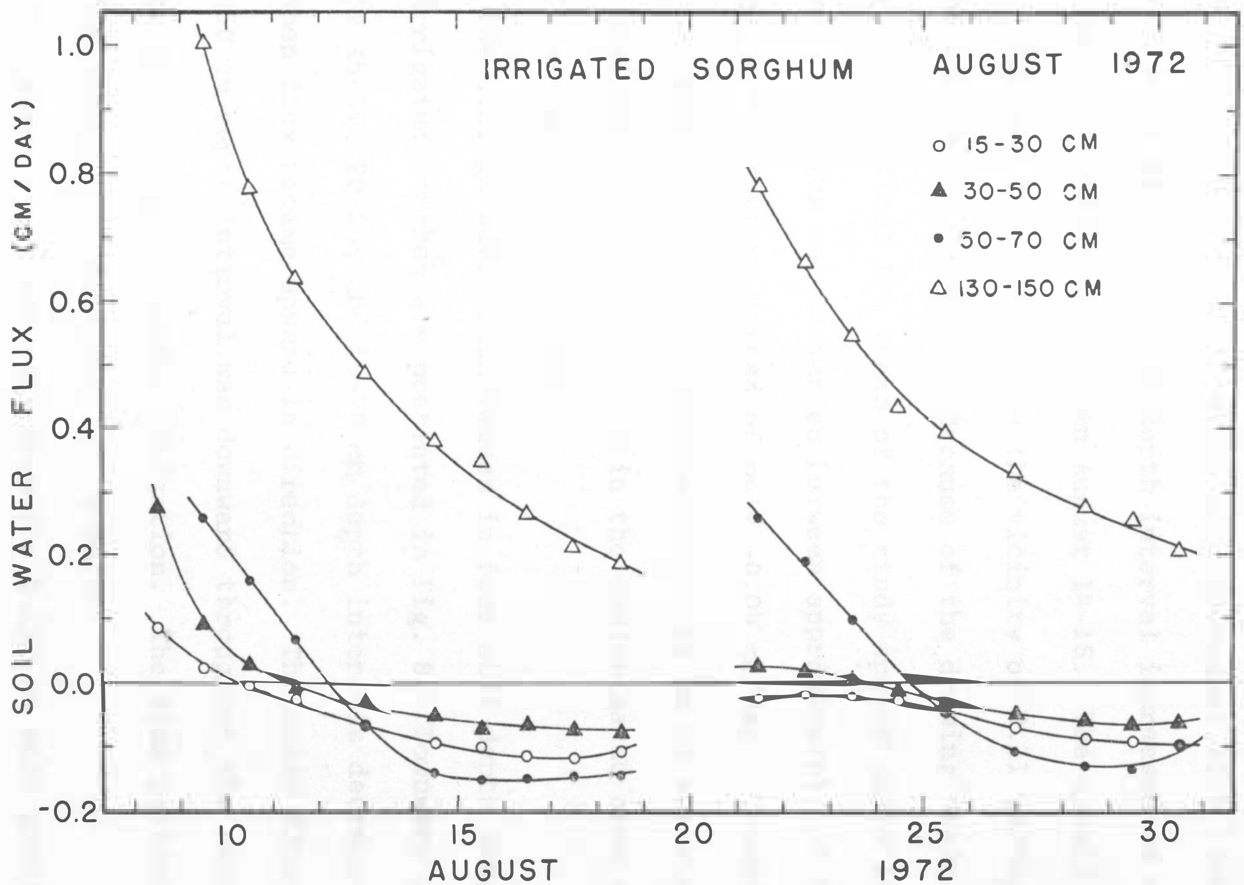

Fig. 8. Soil water flux versus date for four soil depth intervals in irrigated sorghum. Negative values indicate upward water movement.

hydraulic gradient (Fig. 5) and decreasing hydraulic conductivity with decreasing water content. The upward flux of water in the 30-50 cm and 50-70 cm soil layers also decreased with time. Upward water flux in the 130-150 cm depth interval increased to approximately 0.17 cm/day (absolute value) on August 14-15. The upward flux value then decreased and remained in the vicinity of 0.11 cm/day during the remainder of the study. Because of the drawing scale, the cycles in the final two weeks of the study appear quite large. However, the flux values varied between approximately -0.09 and -0.13 cm/day, for a maximum spread of only -0.04 cm/day. Upward flux into the root zone contributed approximately 0.11 cm of water per day of that used in evapotranspiration in the nonirrigated area during the final two weeks of the study.

The average water flux values in four soil depth intervals in the irrigated sorghum are presented in Fig. 8. Downward water flux in the 15-30, 30-50, and 50-70 cm depth intervals decreased to zero and then flux became upward in direction. The water flux in the 130-150 cm depth interval was downward throughout the study, but did decrease with time following irrigation. The flux patterns following the two irrigations were similar in nature.

The water depletion rate from the 0-150 cm soil profile was calculated using water content profiles. Flux corrected to the 150 cm depth was obtained using the average water flux in the 130-150 cm depth interval (Fig. 7 and 8) and a knowledge of water content change. Evapotranspiration rates were then estimated by correcting depletion to account for the water flux at 150 cm (equation 4). The estimated depletion, flux, and evapotranspiration rates are plotted versus date in Fig. 9 and 10.

Figure 9 shows the water loss rates in the nonirrigated sorghum. For all but one date, water was moving upward into the root zone. If evapotranspiration had been estimated with the commonly used methods of neutron scattering or gravimetric sampling while neglecting water flux, evapotranspiration would have been underestimated throughout the study in the nonirrigated area. The evapotranspiration estimates showed a decreasing trend throughout the month-long study.

The water loss rates in the irrigated sorghum are shown in Fig. 10. Water flux at the 150 cm depth was from the root zone throughout the study. Evapotranspiration would have been overestimated if flux had not been taken into account. The evapotranspiration estimates in the irrigated sorghum stayed at a somewhat level trend and did not show the decreasing trend seen in the nonirrigated sorghum.

Mean values of leaf diffusion resistance (LDR) to water vapor transfer are shown versus date in Fig. 11. Measurements were made in each area on six fully developed sorghum leaves exposed to sunlight at approximately 1530 hours CDT on the date indicated. The mean values of the six readings ± SD are shown.

Illumination and leaf water potential are usually considered the primary factors altering stomatal aperture in field studies.

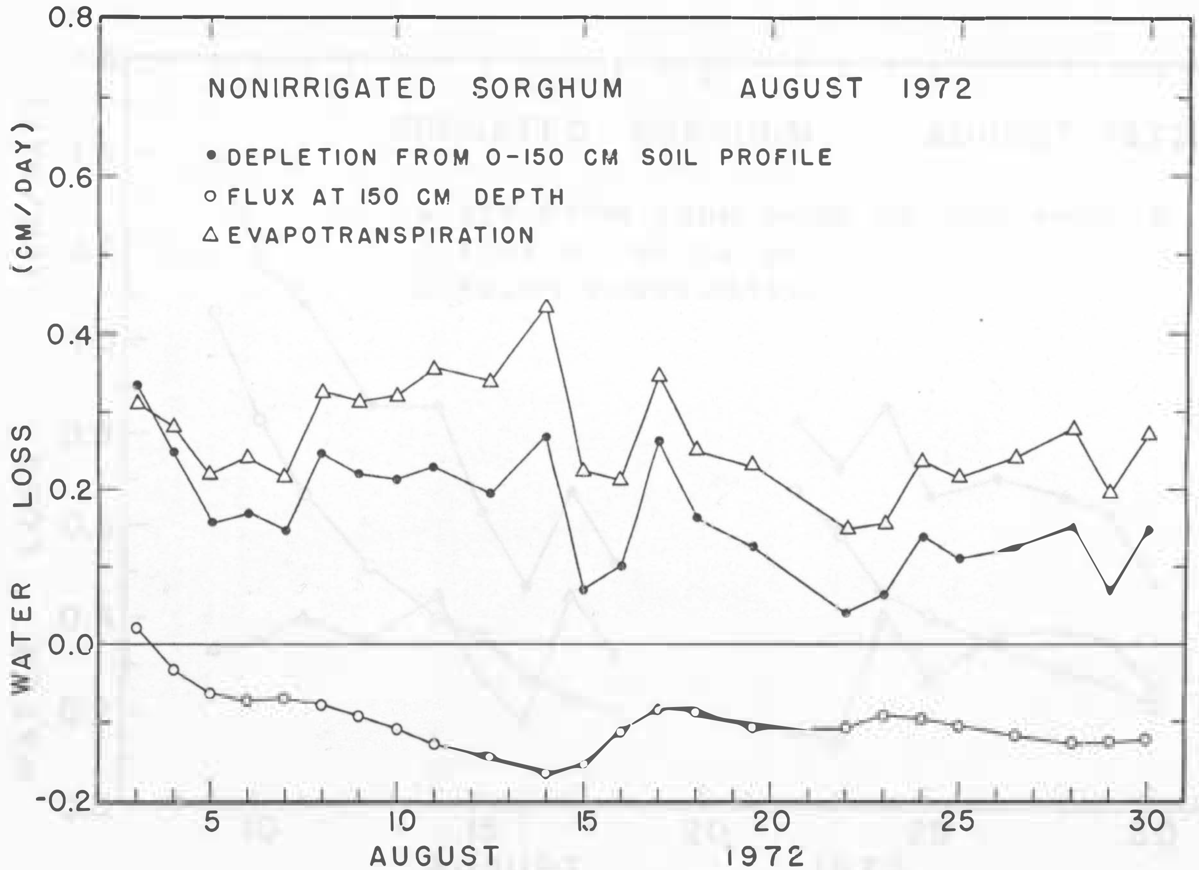

Fig. 9. Water loss rate in cm/day versus date in the nonirrigated sorghum. Water is lost by evapotranspiration and flux at the 150 cm depth. The sum of the two is the total depletion rate from the 0 to 150 cm soil profile. Negative values of soil water flux indicate upward water movement.

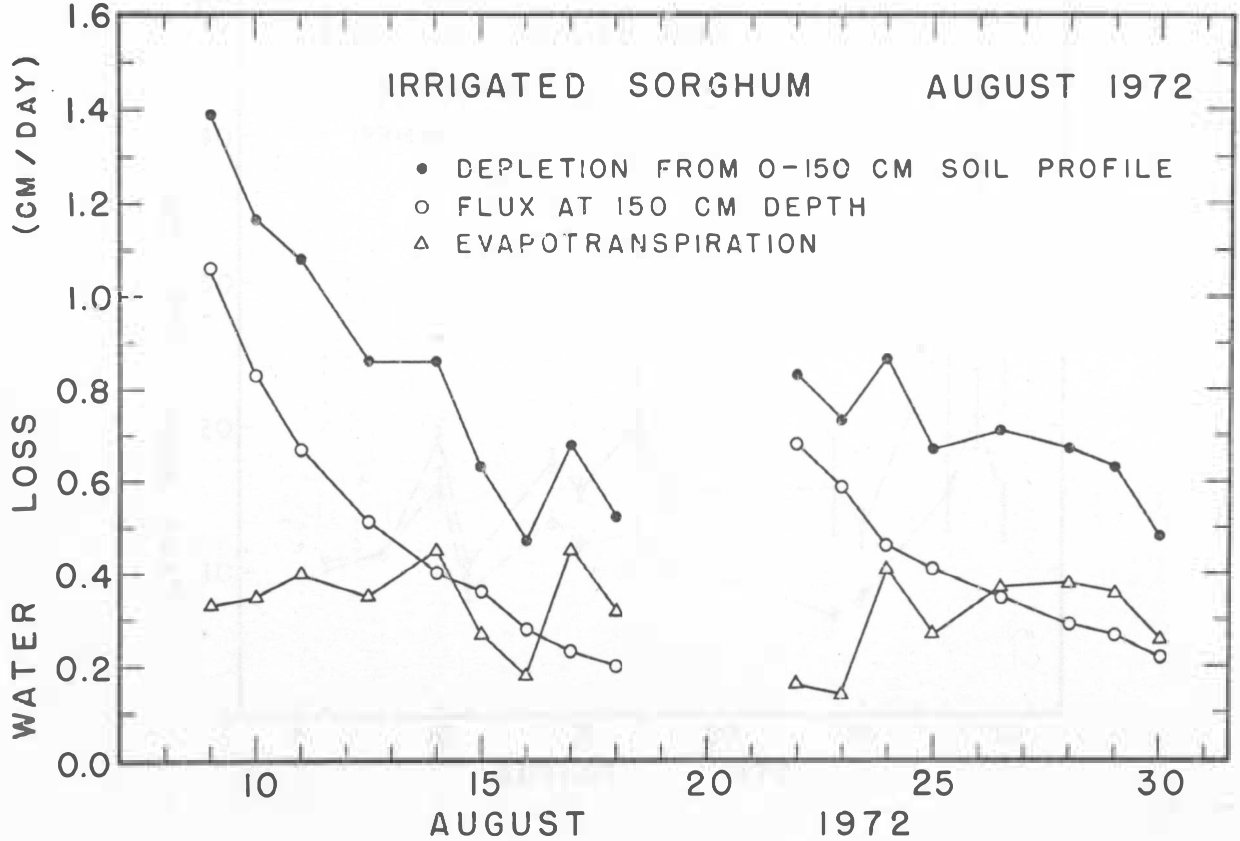

Fig. 10. Water loss rate in cm/day versus date in the irrigated sorghum. Water is lost by evapotranspiration and flux at the 150 cm depth. The sum of the two is the total depletion rate from the 0 to 150 cm soil profile.

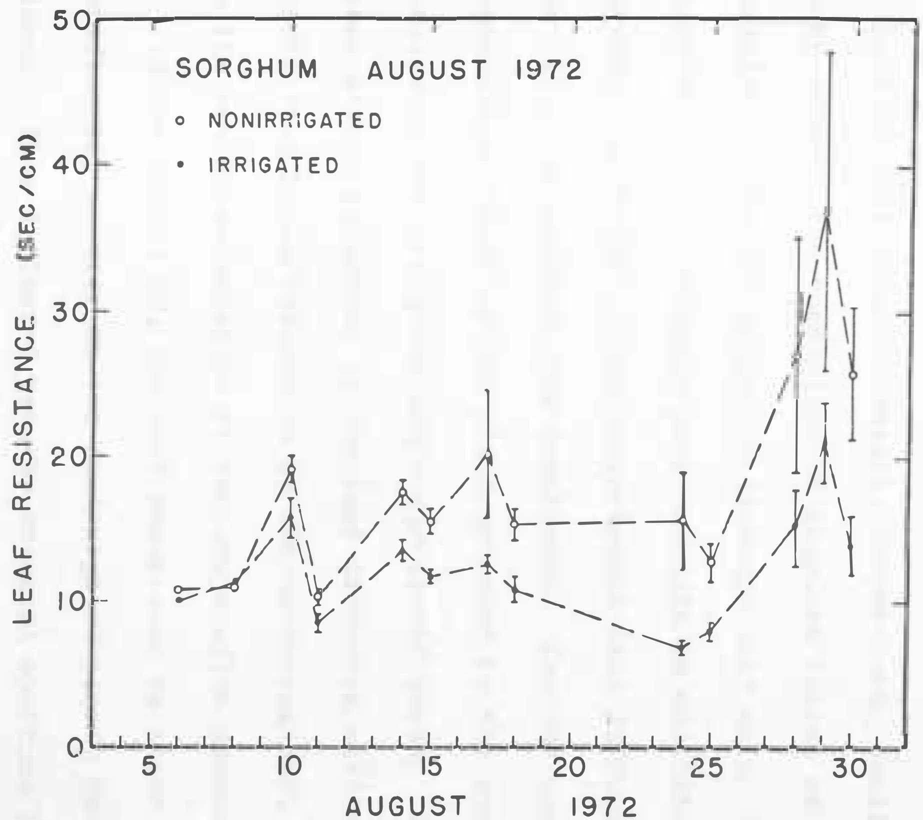

Fig. 11. Leaf diffusion resistance versus date for the nonirrigated and irrigated sorghum. Each datum point represents a mean of six measurements. The vertical interval shown represents the mean value ± SD.

The measurements were taken on leaves fully exposed to sunlight at approximately the same time each day to reduce the fluctuations caused by illumination variance. This was done in an attempt to obtain leaf diffusion resistance measurements as a function of the internal water status of the leaves. However, due to the complex actions of leaf water potential, temperature, sunlight, and leaf age among others, the comparison of absolute values of leaf diffusion resistance from day to day to evaluate leaf water deficit is suspect. Therefore, it is probably more accurate to evaluate the differences between the irrigated and nonirrigated leaf diffusion resistances than it is to evaluate the magnitudes. For the same date, the evaporative demand on the plant produced by the atmosphere should be similar in the irrigated and nonirrigated areas. Differences in leaf water status indicated by the leaf diffusion resistance measurements should then be an indication of the different soil water availability in the two areas relative to the evaporative demand.

After August 10, the leaf resistance to vapor transfer was consistently greater in the nonirrigated plants than in the irrigated plants. This indicated greater stomatal aperture in the irrigated plants, probably caused by greater soil water availability and uptake in the irrigated area. Irrigations were on August 7 (12 cm) and on August 19 (8 cm). During the first irrigation cycle, the average difference between nonirrigated and irrigated LDR was 4.1 sec/cm, with the difference exhibiting an increasing trend with time. During the same time interval, the average difference between nonirrigated and irrigated soil water pressure at the 50 cm depth was -330 cm of water (Fig. 3 and 4). The average difference between nonirrigated and irrigated LDR during the second irrigation cycle was 10.6 sec/cm. The average soil water pressure difference during the second irrigation cycle at the 50 cm depth was -525 cm of water. Therefore, it was apparent that during the second irrigation cycle, the greater difference in soil water availability was accompanied by a greater difference in LDR measurements in comparison to the first irrigation cycle. The SD data of Fig. 11 indicate an increase in variability of LDR measurements as leaf resistance measurements increase. Aston and van Bavel (1972) discussed the possibility of using canopy temperature variability within a field to indicate water deficits. The data of Fig. 11 and Aston and van Bavel (1972) do suggest a differential response of plants to water stress, the differential increasing as stress increases.

Evapotranspiration rates estimated using tensiometer data from the irrigated and nonirrigated areas are presented in Fig. 12. The plot is presented to aid in visual analysis of the ET rates presented in Fig. 9 and 10. During the first irrigation cycle, the nonirrigated ET rates were slightly lower than the irrigated ET rates on eight out of nine days. During the second irrigation cycle, the nonirrigated ET rates were much lower on five out of eight days. On August 22 and 23 a low evaporative demand was placed upon the crop by the atmosphere; August 22 had a mean hourly maximum temperature at 80 cm of 22.5 C and a mean hourly maximum

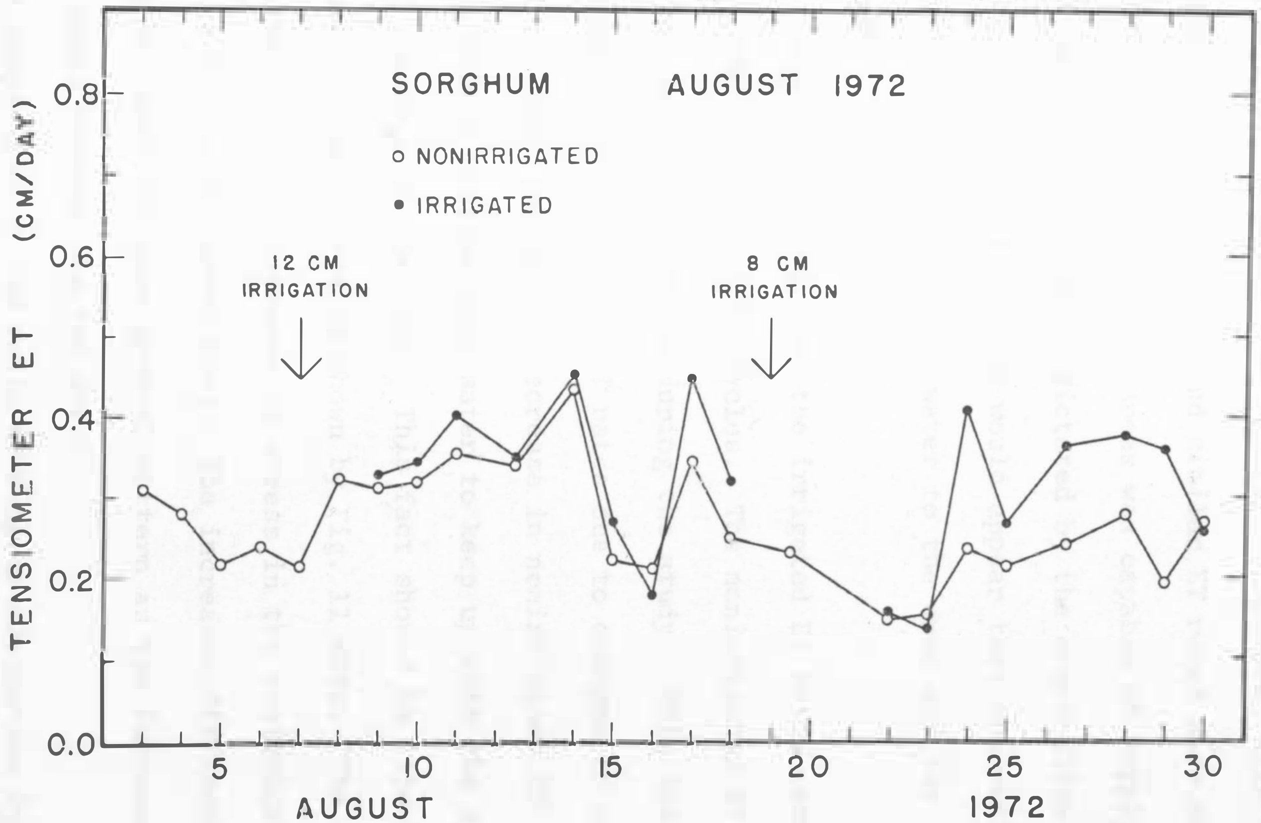

Fig. 12. Evapotranspiration estimated using tensiometer data versus date for the nonirrigated and irrigated sorghum.

global radiation value of 0.9 ly/min, and August 23 had a mean hourly maximum temperature at 80 cm of 22.0 C and a mean hourly maximum global radiation value of 0.5 ly/min. Therefore, with the low evaporative demand, the low and similar ET rates were not surprising. Apparently, the soil in both areas was capable of supplying sufficient amounts of water as dictated by the evaporative demand. On the dates of August 24-29, it would appear that the nonirrigated soil could not supply enough water to the crop and the lower ET rates resulted.

It should be noted that the irrigated ET rates were similar in each of the two irrigation cycles. The nonirrigated ET rates showed a general decrease in value during the study. This indicates there was no change in irrigated ET rates due to changes in available soil water, but does indicate a decrease in nonirrigated ET rates due to insufficient available soil water to keep up with the evaporative demand placed upon the crop. This fact should be illustrated by an increase in leaf stress as shown by Fig. 11 data. The LDR data indicates a gradual increase in stress in the nonirrigated area relative to the irrigated area. The increased difference in LDR values followed the same general pattern as the increased difference in ET rates between the two areas.

A comparison of the ratio of evapotranspiration by tensiometer to pan evaporation versus pan evaporation values for the irrigated and nonirrigated sorghum areas is presented in Fig. 13. A simple linear regression equation was determined by the least squares method

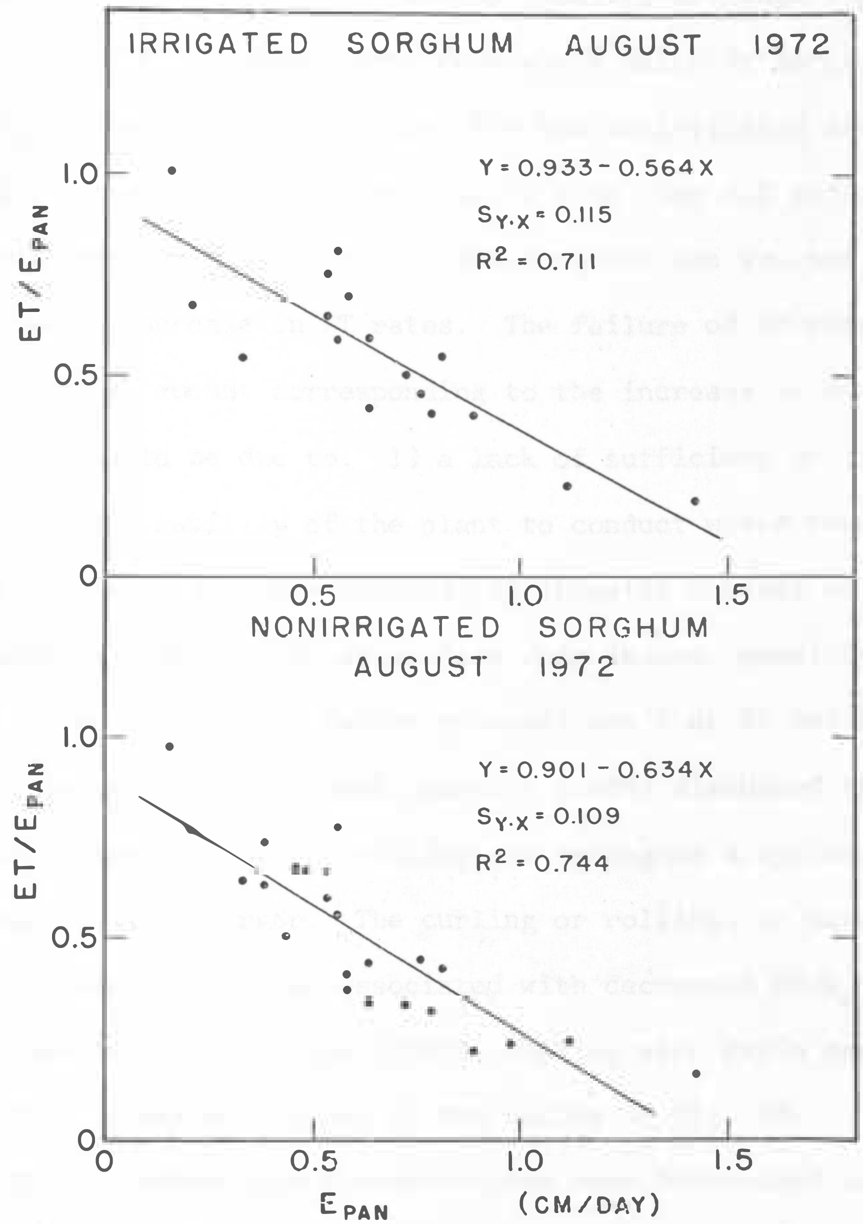

Fig. 13. Ratio of evapotranspiration by tensiometer to pan evaporation versus pan evaporation for the irrigated (upper) and nonirrigated (lower) sorghum.

for the data from each area. The regression and correlation analysis of the data yielded similar results, although the regression equation for the irrigated area does yield slightly larger estimates of ET/E_{pan} than does the equation for the nonirrigated area.

The ratios in Fig. 13 are usually less than 1.0 and indicate that an increase in evaporation rate from the pan was not accompanied by a similar increase in ET rates. The failure of ET rates to increase in an amount corresponding to the increase in evaporation from a pan could be due to: 1) a lack of sufficient available soil water; 2) the inability of the plant to conduct water from the root to the leaves in adequate amounts; 3) stomatal control acting as a regulator to moderate the water loss from leaves, possibly as a result of an atmospheric factor or condition 1 or 2; and 4) changes in leaf geometry. Pruitt and Lourence (1968) discussed the occurrence of grass leaves curling or rolling and taking on a cylindrical shape, with some loss of turgor. The curling or rolling, on days of high advection conditions, was associated with decreased ET/E_{pan} ratios. Hanks, Gardner, and Florian (1968), working with grain sorghum, found ET/E_{pan} values similar to the ratios of Fig. 13.

Hourly sorghum canopy temperatures were determined using a Barnes Infrared Thermometer. Sorghum canopy temperature data, along with air temperature data at the 80 cm elevation, are plotted in Fig. 14, 15, 16, 17, 18, and 19. Data for air and canopy in both the irrigated and nonirrigated areas are plotted for times when the system was moving over both areas.

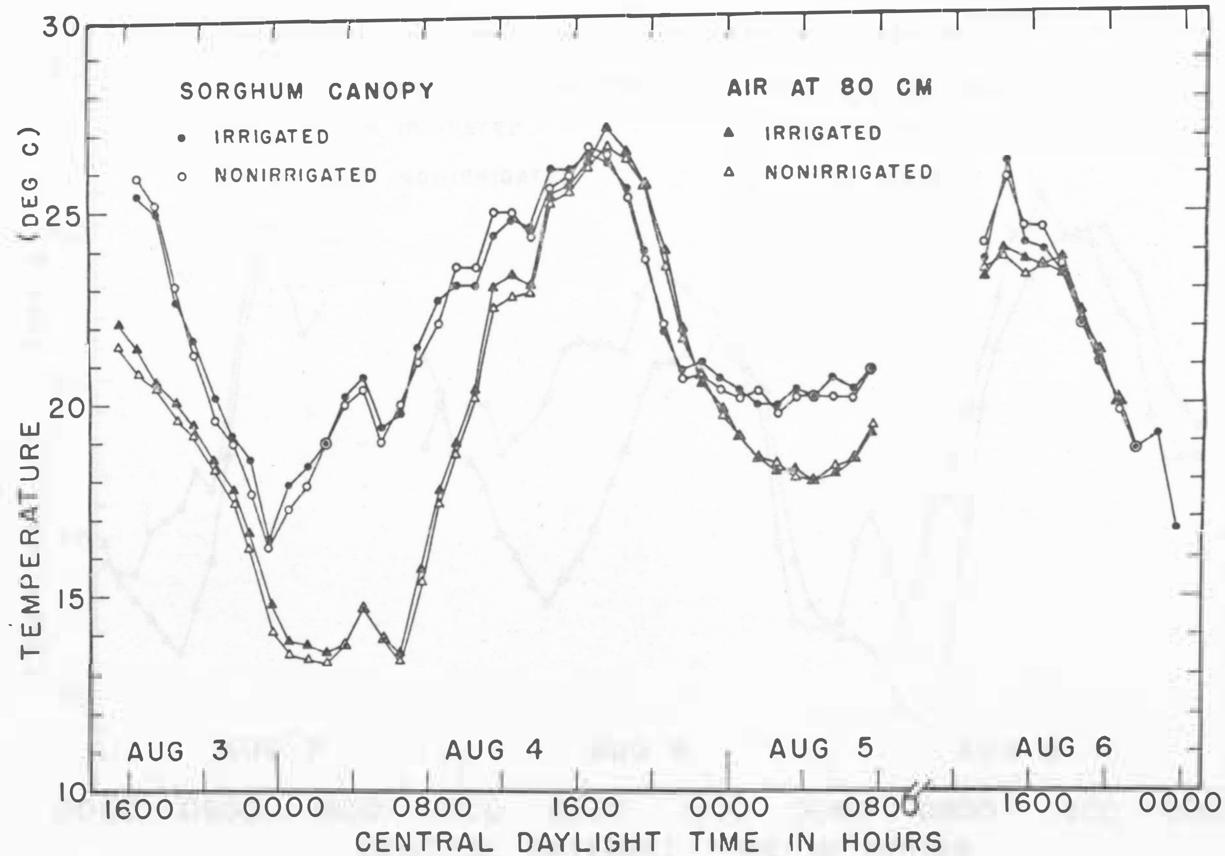

Fig. 14. Hourly air and sorghum cancpy temperatures on August 3, 4, 5, and 6, 1972.

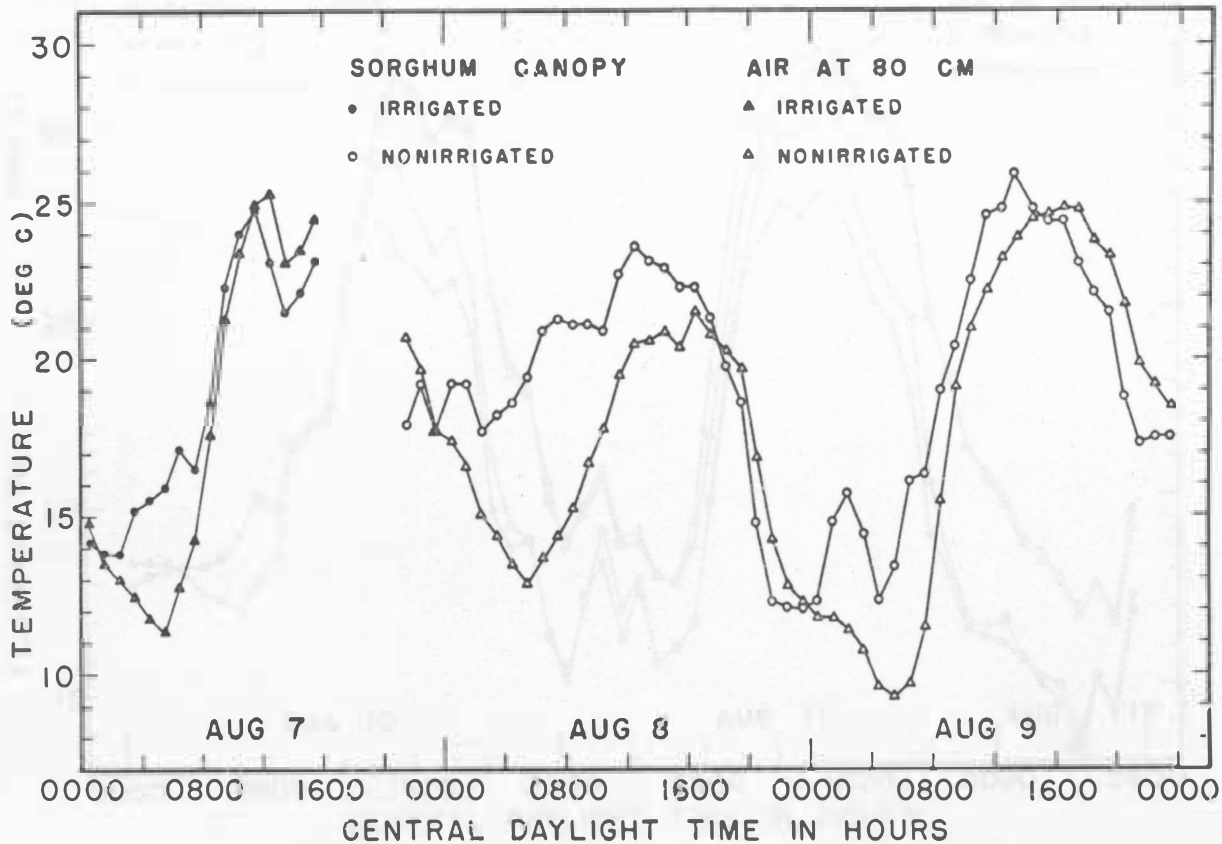

Fig. 15. Hourly air and sorghum canopy temperatures on August 7, 8, and 9, 1972.

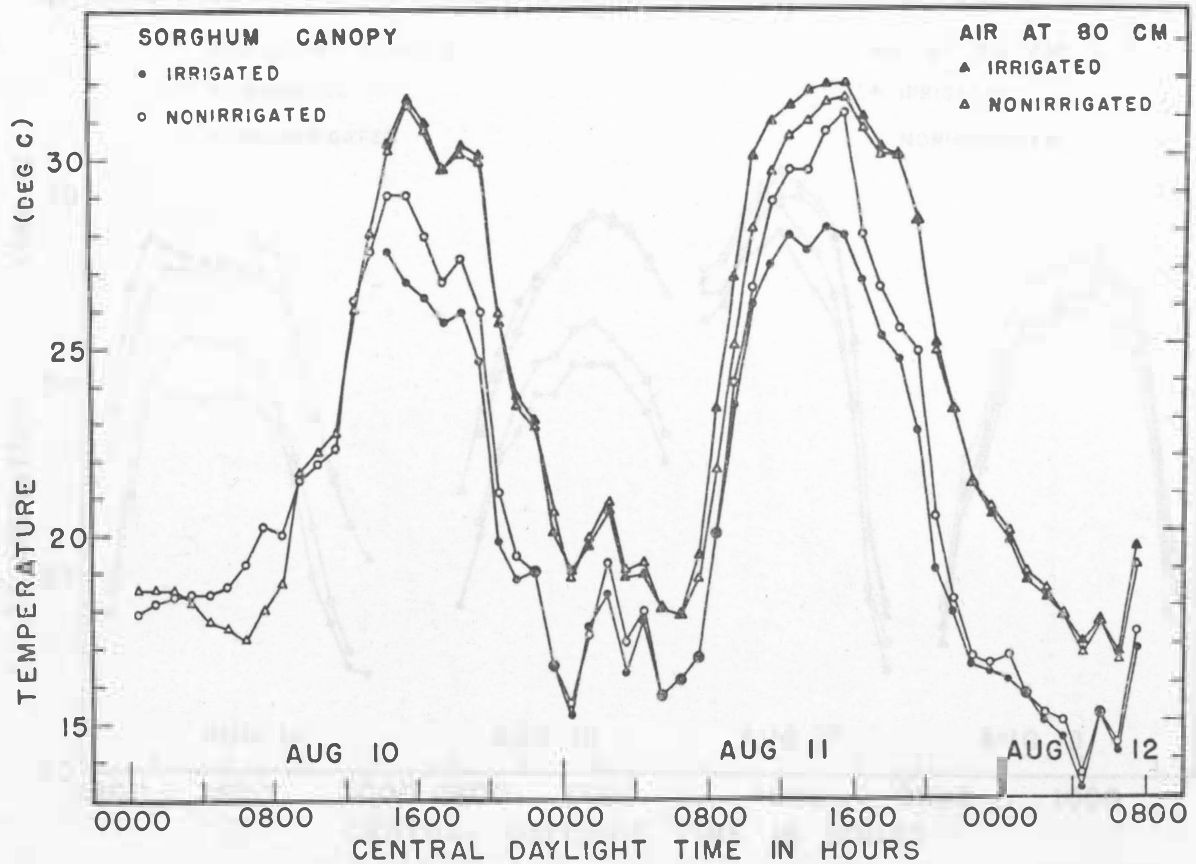

Fig. 16. Hourly air and sorghum canopy temperatures on August 10, 11, and 12, 1972.

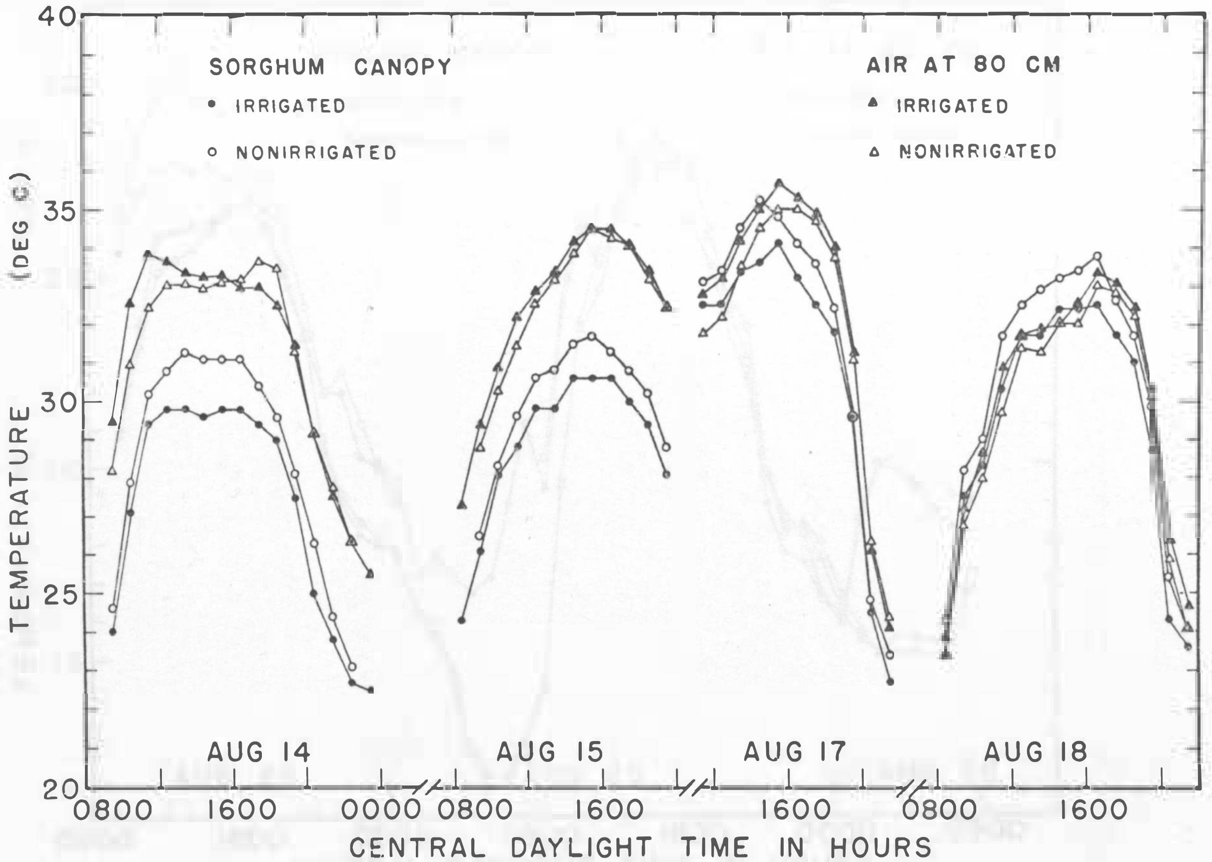

Fig. 17. Hourly air and sorghum canopy temperatures on August 14, 15, 17, and 18, 1972.

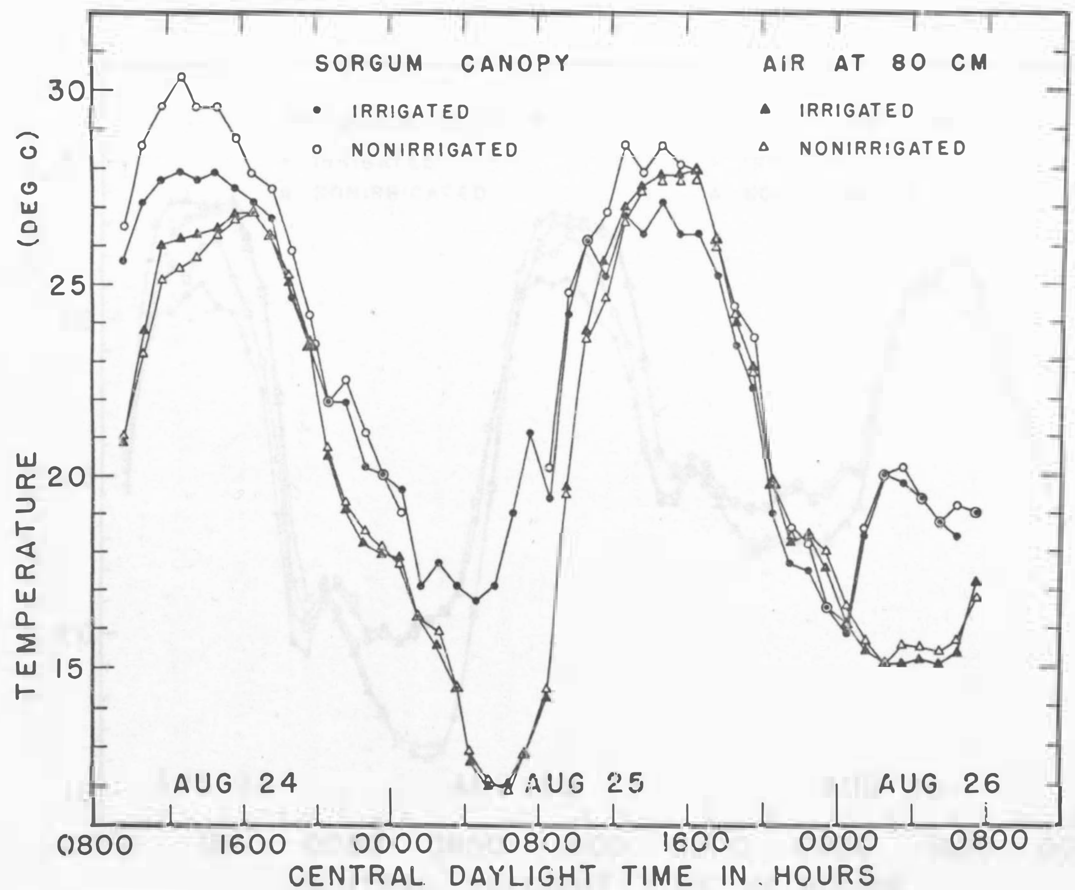

Fig. 18. Hourly air and sorghum canopy temperatures on August 24, 25, and 26, 1972.

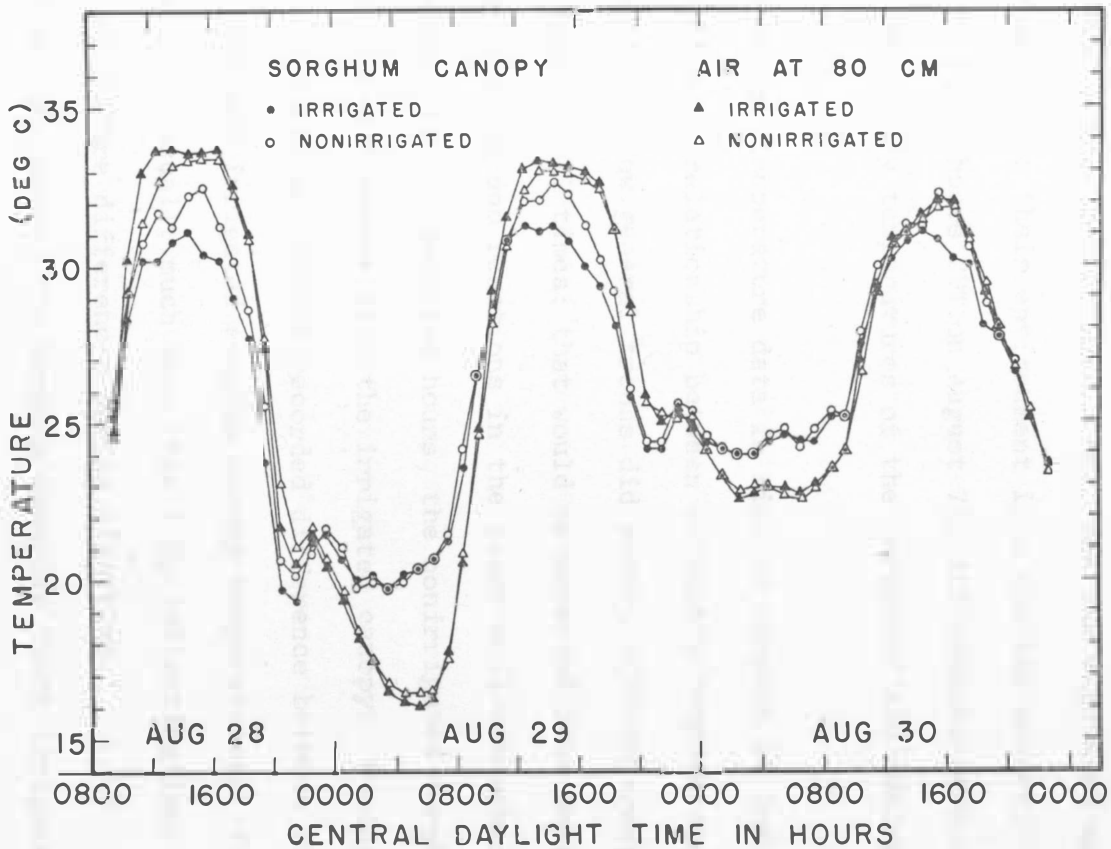

Fig. 19. Hourly air and sorghum canopy temperatures on August 28, 29, and 30, 1972.

The data in Fig. 14 were taken before any irrigation water was applied. The figure illustrates good agreement between irrigated and nonirrigated areas for both the air and canopy temperatures. This indicates that before irrigation, the two vegetated surfaces were responding to their environment in a similar manner. After irrigation (1600 hours CDT on August 7), differences were noted between the canopy temperatures of the irrigated and nonirrigated areas.

The canopy temperature data in Fig. 14 through 19 indicate a very complicated relationship between a plant's temperature and its environment. A few general trends did occur, with apparently none holding true at all times; that would be expected considering the number of actions and reactions in the plant-soil-atmosphere environment. During daylight hours, the nonirrigated sorghum canopy was usually 1-3 C warmer than the irrigated canopy. During nighttime hours, there was little recorded difference between the nonirrigated and irrigated sorghum canopy temperatures. The difference was usually much less than 1 C, indicating lack of real canopy temperature differences during nighttime.

In daylight hours, the sorghum canopies (both irrigated and nonirrigated) were usually cooler than the air temperature. The crop canopy dissipates energy through the processes of transpiration, radiation, and convection. The degree to which these energy dissipating processes occur greatly affects the plant temperature. There was much variation in the magnitude of daytime air minus canopy temperatures, but 3-5 C differences were often recorded. This agrees with work reported by van Bavel and Ehrler (1968), that sorghum foliage was several degrees cooler than ambient air during the middle of the day. On cool days the reverse was true, with the canopy being warmer than air at midday. Two of the days exhibiting canopy temperatures greater than air temperatures were August 24 and 25. On August 24, the air temperatures were exceeded by both the nonirrigated and irrigated canopy temperatures. Canopy temperatures were 2-5 C warmer than air temperatures. On August 25, the non-irrigated canopy temperatures exceeded air temperatures at mid-afternoon, but the irrigated canopy temperature was less than air temperature. Air temperatures were lower than usual on both of those days.

Late in the afternoon, approximately 1600 hours CDT, the canopy temperatures would start declining. The decline coincided with the sharp decrease in incoming shortwave radiation noted at approximately 1600-1700 hours. The initiation of air temperature decline was usually 1 to 2 hours after the canopy temperature decline. That would be expected because the canopy absorbs radiation which aids in heating the air; as radiation drops off, the canopy responds quickly and the air then reflects the decrease in canopy absorption by dropping in temperature.

During early morning hours, 0000 to 0800 hours CDT, the canopy temperature was usually greater than the air temperature. The difference was often as much as 5-6 C. Rosenberg and Powers (1970) reported alfalfa temperatures greater than air temperatures during nighttime. Apparently, the canopy with its higher heat capacity than air, decreased in temperature until approximately 0000-0100 hours and then leveled off somewhat, while the air temperature continued to decrease until approximately 0600 hours. On the nights of August 10 and 11, the canopy temperatures decreased to a cooler temperature than the air. That agrees with diurnal work reported by Ehrler and van Bavel (1967), van Bavel and Ehrler (1968), and Carlson (1972). It might be noted that those three articles contain a total of four diurnal temperature cycles. In view of the many varied responses evident in the data of this thesis, it would appear that more than one diurnal cycle would be needed before meaningful trends of canopy temperature could be recognized. No measurable reason for the nighttime patterns observed on August 10 and 11 could be found from the data. There appeared to be no divergences from usual nighttime data of air temperature, soil temperature, and wind speed. There could have been differences due to atmospheric humidity levels or possibly due to plant growth stage. Humidity data were not collected during the nighttime and the point can not be checked further.

Incoming shortwave radiation and canopy temperature were recorded continuously during a 20-minute time span on August 30. The Barnes was stationary and monitored irrigated sorghum canopy temperatures while radiation was measured at 12-second intervals using the data logger. The plots of incoming shortwave radiation and canopy temperature versus time are presented in Fig. 20. During the study

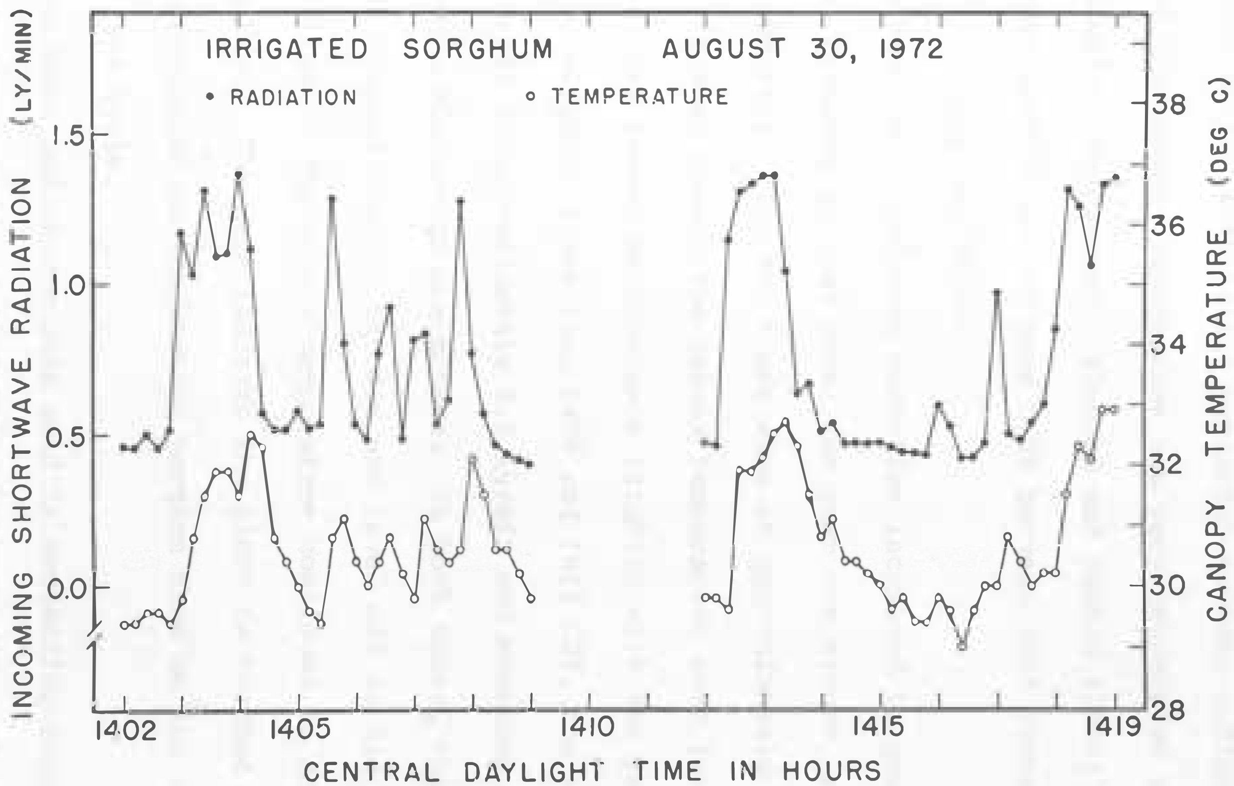

Fig. 20. Variations in incoming shortwave radiation and canopy temperature versus time in irrigated sorghum.

time, there was little measurable change in atmospheric conditions other than radiation. Air temperature during the study was at approximately 30.8 C with little variation evident. Figure 20 illustrates that canopy temperature was very responsive to a change in its radiation environment. Wiegand and Namken (1966) presented a correlation coefficient of near 0.95 between leaf temperature of cotton and incoming radiation.

There were two times when radiation increased to greater than 1.0 ly/min, remained at that level for over one minute, and then decreased abruptly. The two times were at approximately 1403 and 1412 CDT. In both cases, the canopy temperature soon increased sharply and then tended to fluctuate slightly with the radiation changes. At slightly later than 1404 and 1413 CDT, the radiation dropped sharply to approximately 0.5 ly/min and remained near constant for a minimum of one minute. In both cases, the canopy temperature dropped sharply but did not level off as did the radiation values. The canopy temperature continued to decrease at a decreasing rate. The data indicate the plant to respond more rapidly to radiation on the heating portion than on the cooling portion of the cycle.

Microclimate and canopy data used in estimating evapotranspiration are presented in Tables 4 through 12. All values listed are the mean values for an hour. The ET predictive equations were not used on other dates because of incomplete data. The use of nine dates provided approximately 100 hours of irrigated and 100 hours

Table 4. Mean hourly data used in calculation of ET estimates. Data presented for irrigated and nonirrigated sorghum, August 11, 1972, Redfield, S. D.

Mean time (CDT)	Incoming shortwave radiation (ly/min)	Wind speed (m/sec)	Net radiation (ly/min)		Soil heat flux (ly/min)		Bowen ratio		Vapor pressure deficit (mb)		Air temp at 180 cm elev (Deg C)		Canopy temp (Deg C)	
			Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir
0830	0.37	1.3	.17	.17	.0	.0	0.33	0.09	3.7	4.1	23.1	21.5	20.0	20.0
0930	0.61	1.8	.37	.38	-.03	-.02	0.39	0.16	6.6	6.9	26.5	24.5	23.4	24.0
1030	0.83	1.8	.56	.61	-.05	-.03	0.52	0.05	9.4	9.7	29.6	27.9	26.1	26.5
1130	1.00	2.2	.72	.82	-.03	-.05	0.09	0.05	12.2	11.9	30.8	29.4	27.1	28.8
1230	1.11	2.5	.81	.90	-.11	-.05	0.0	0.05	14.3	13.3	31.2	30.3	27.9	29.6
1330	1.17	1.6	.87	.95	-.13	-.06	0.28	0.18	16.4	14.6	31.4	30.4	27.5	29.6
1430	1.09	1.1	.76	.90	-.10	-.06	0.16	0.15	17.6	15.8	31.7	31.1	28.1	30.6
1530	0.98	1.3	.82	.92	-.11	-.07	0.0	0.08	18.1	16.9	31.9	31.4	27.9	31.1
1630	0.64	0.9	.50	.55	-.10	-.06	-0.27	-0.16	18.7	18.0	31.4	30.8	26.7	27.9
1730	0.40	0.7	.26	.29	-.08	-.06	-0.46	1.08	19.3	19.1	30.8	30.5	25.2	26.5
1830	0.43	1.1	.29	.29	-.07	-.05	-0.43	0.86	17.8	17.5	30.5	30.4	24.6	25.4
1930	0.21	1.3	.11	.09	-.05	-.03	-1.14	-1.30	13.0	13.7	29.0	28.7	22.7	24.8

Table 5. Mean hourly data used in calculation of ET estimates. Data presented for irrigated and nonirrigated sorghum, August 14, 1972, Redfield, S. D.

Mean time (CDT)	Incoming shortwave radiation (ly/min)	Wind speed (m/sec)	Net radiation (ly/min)		Soil heat flux (ly/min)		Bowen ratio		Vapor pressure deficit (mb)		Air temp at 180 cm elev (Deg C)		Canopy temp (Deg C)	
			Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir
0930	0.60	1.8	.39	.35	-.02	-.02	.05	-.16	8.8	8.7	29.4	28.3	24.0	24.6
1030	0.81	2.5	.58	.54	-.06	-.03	.19	-.05	13.0	12.9	32.2	31.1	27.1	27.9
1130	0.98	2.5	.75	.72	-.13	-.04	.16	-.06	17.2	17.3	33.5	32.8	29.4	30.2
1230	1.09	3.4	.85	.85	-.21	-.05	-.07	-.02	20.3	20.9	33.9	33.2	29.8	30.8
1330	1.15	4.0	.90	.91	-.13	-.05	.0	.0	21.8	21.9	33.4	33.1	29.8	31.3
1430	1.13	4.7	.88	.91	-.08	-.05	-.09	-.06	23.2	23.0	33.6	33.2	29.6	31.1
1530	1.03	4.9	.80	.84	-.08	-.05	-.13	-.04	23.9	23.5	33.7	33.3	29.8	31.1
1630	0.88	4.7	.68	.70	-.07	-.05	-.19	-.04	23.1	23.2	33.6	33.3	29.8	31.1
1730	0.67	4.7	.50	.52	-.06	-.05	-.13	-.14	22.3	23.1	33.3	33.1	29.4	30.4
1830	0.43	4.7	.30	.30	-.04	-.04	-.20	-.04	20.8	22.8	32.9	32.6	29.0	29.6
1930	0.19	3.1	.10	.09	-.03	-.03	-.41	-.15	16.5	17.6	32.0	31.7	27.5	28.1

Table 6. Mean hourly data used in calculation of ET estimates. Data presented for irrigated and nonirrigated sorghum, August 15, 1972, Redfield, S. D.

Mean time (CDT)	Incoming shortwave radiation (ly/min)	Wind speed (m/sec)	Net radiation (ly/min)		Soil heat flux (ly/min)		Bowen ratio		Vapor pressure deficit (mb)		Air temp at 180 cm elev (Deg C)		Canopy temp (Deg C)	
			Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir
0830	0.37	4.0	.19	.21	.0	.0	.0	-.05	7.5	7.6	27.3	26.8	24.3	25.2
0930	0.61	4.5	.43	.41	-.01	-.01	.0	.0	9.6	9.6	29.4	28.8	26.1	26.5
1030	0.77	4.5	.58	.56	-.04	-.02	.0	.0	11.8	11.7	30.9	30.3	28.1	28.3
1130	0.94	4.5	.73	.73	-.07	-.03	-.09	-.06	13.9	13.9	32.3	31.6	28.8	29.6
1230	1.05	4.7	.84	.85	-.11	-.04	.14	.10	16.2	16.3	32.7	32.4	29.8	30.6
1330	1.10	5.4	.88	.90	-.10	-.05	.0	.08	18.4	18.8	33.4	33.0	29.8	30.8
1430	1.08	5.8	.85	.90	-.09	-.05	.0	.07	20.7	21.2	34.2	34.1	30.6	31.5
1530	0.99	5.1	.78	.82	-.09	-.05	-.11	.03	22.3	22.8	34.7	34.4	30.6	31.7
1630	0.83	5.1	.65	.67	-.09	-.05	-.11	-.11	23.4	23.7	34.7	34.6	30.6	31.3
1730	0.63	5.1	.49	.49	-.07	-.05	-.29	-.16	24.4	24.5	34.6	34.5	30.0	30.8
1830	0.40	4.5	.28	.27	-.06	-.04	-.32	-.25	24.7	23.6	33.9	33.8	29.4	30.2
1930	0.17	3.1	.09	.06	-.04	-.03	-.49	-.19	19.8	19.7	32.7	32.7	28.1	28.8

Table 7. Mean hourly data used in calculation of ET estimates. Data presented for irrigated and nonirrigated sorghum, August 18, 1972, Redfield, S. D.

Mean time (CDT)	Incoming shortwave radiation (ly/min)	Wind speed (m/sec)	Net radiation (ly/min)		Soil heat flux (ly/min)		Bowen ratio		Vapor pressure deficit (mb)		Air temp at 180 cm elev (Deg C)		Canopy temp (Deg C)	
			Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir
0830	0.24	2.1	.10	.10	.02	.0	.0	.21	5.4	6.0	23.8	23.3	23.4	24.3
0930	0.58	2.1	.40	.39	-.01	-.01	.11	.65	8.1	8.4	26.6	26.2	27.5	28.2
1030	0.69	1.1	.51	.49	-.04	-.02	.36	.21	10.7	11.0	28.2	27.6	28.3	29.0
1130	0.90	1.1	.69	.64	-.07	-.03	.32	.30	13.4	13.6	30.0	29.1	30.3	31.7
1230	1.07	1.3	.83	.80	-.11	-.04	.0	.26	15.6	15.2	31.8	30.8	31.7	32.5
1330	1.10	1.6	.85	.84	-.12	-.04	.0	.0	17.8	15.9	31.9	31.3	31.7	32.9
1430	1.07	1.6	.83	.83	-.11	-.04	-.04	.09	19.9	16.7	32.1	31.8	32.4	33.2
1530	0.97	1.6	.76	.75	-.11	-.05	.07	-.08	20.7	18.2	32.4	32.2	32.4	33.4
1630	0.82	1.1	.63	.61	-.10	-.04	.03	.0	21.4	19.8	33.3	33.0	32.5	33.8
1730	0.62	0.9	.47	.43	-.09	-.04	-.16	.16	22.1	21.4	33.7	33.2	31.7	32.7
1830	0.40	0.9	.28	.26	-.06	-.03	-.17	-.21	19.8	20.8	33.0	32.8	31.0	31.7
1930	0.16	0.9	.08	.05	-.04	-.03	-.28	-.26	14.7	15.8	31.0	30.7	28.7	29.9

Table 8. Mean hourly data used in calculation of ET estimates. Data presented for irrigated and nonirrigated sorghum, August 24, 1972, Redfield, S. D.

Mean time (CDT)	Incoming shortwave radiation (ly/min)	Wind speed (m/sec)	Net radiation (ly/min)		Soil heat flux (ly/min)		Bowen ratio		Vapor pressure deficit (mb)		Air temp at 180 cm elev (Deg C)		Canopy temp (Deg C)	
			Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir
0930	0.58	0.7	.33	.35	.0	.0	-0.21	1.04	4.8	5.5	21.6	20.2	25.6	26.5
1030	0.79	1.6	.50	.57	-.04	-.01	-0.04	0.43	7.7	8.6	23.9	22.6	27.1	28.6
1130	0.99	2.5	.68	.77	-.08	-.02	0.12	0.33	10.8	11.8	25.7	24.4	27.7	29.6
1230	1.10	2.5	.79	.89	-.13	-.03	0.16	0.18	13.9	15.0	25.9	25.0	27.9	30.4
1330	1.15	1.8	.81	.91	-.11	-.03	0.12	0.25	16.1	16.9	26.1	25.1	27.7	29.6
1430	1.12	1.8	.79	.89	-.09	-.04	0.20	0.34	17.2	17.4	26.1	25.5	27.9	29.6
1530	1.02	1.8	.73	.80	-.11	-.04	0.10	0.25	17.5	17.8	26.6	26.2	27.5	28.8
1630	0.86	2.0	.59	.65	-.07	-.04	0.13	0.20	17.3	17.7	27.1	26.6	27.1	27.9
1730	0.55	2.0	.38	.40	-.05	-.03	-0.18	0.09	16.9	17.6	26.6	26.2	26.7	27.5
1830	0.40	2.7	.24	.23	-.02	-.02	-0.98	0.0	15.7	16.4	25.6	25.2	24.6	25.9
1930	0.15	2.0	.06	.04	.01	-.02	-1.95	-0.98	13.8	14.1	23.7	23.7	23.4	24.2

Table 9. Mean hourly data used in calculation of ET estimates. Data presented for irrigated and nonirrigated sorghum, August 25, 1972, Redfield, S. D.

Mean time (CDT)	Incoming shortwave radiation (ly/min)	Wind speed (m/sec)	Net radiation (ly/min)		Soil heat flux (ly/min)		Bowen ratio		Vapor pressure deficit (mb)		Air temp at 180 cm elev (Deg C)		Canopy temp (Deg C)	
			Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir
0830	0.20	0.5	.07	.06	.08	.02	-3.25	.49	1.3	0.5	14.7	14.1	19.4	20.2
0930	0.60	2.2	.38	.38	.02	.01	-2.28	.33	3.7	3.4	20.3	19.2	24.2	24.8
1030	0.81	2.5	.53	.58	-.03	-.01	-0.18	.65	7.8	7.6	24.1	22.9	26.1	26.1
1130	0.94	2.7	.65	.73	-.07	-.02	0.07	.29	12.1	11.9	25.4	24.3	25.2	26.9
1230	1.15	2.9	.85	.95	-.13	-.03	0.07	.19	14.3	14.9	26.7	26.2	26.7	28.6
1330	1.16	2.9	.83	.95	-.12	-.03	0.0	.18	16.3	17.5	27.5	26.9	26.3	27.9
1430	1.12	2.5	.80	.92	-.11	-.05	-0.04	.08	17.0	18.0	27.9	27.5	27.1	28.6
1530	0.87	2.7	.70	.80	-.13	-.05	0.0	.19	17.5	18.1	27.8	27.3	26.3	28.1
1630	0.86	2.9	.62	.67	-.09	-.04	-0.03	.20	17.8	18.2	28.0	27.5	26.3	27.9
1730	0.63	3.4	.45	.45	-.05	-.03	-0.04	.0	17.0	17.4	26.2	26.0	25.2	26.1
1830	0.40	3.3	.25	.23	-.02	-.02	-0.05	.11	14.4	14.9	24.2	24.1	23.4	24.4
1930	0.20	2.7	.11	.09	.01	-.02	-0.14	.0	11.9	12.6	23.0	22.8	22.3	23.6

Table 10. Mean hourly data used in calculation of ET estimates. Data presented for irrigated and nonirrigated sorghum, August 28, 1972, Redfield, S. D.

Mean time (CDT)	Incoming shortwave radiation (ly/min)	Wind speed (m/sec)	Net radiation (ly/min)		Soil heat flux (ly/min)		Bowen ratio		Vapor pressure deficit (mb)		Air temp at 180 cm elev (Deg C)		Canopy temp (Deg C)	
			Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir
0930	0.54	0.4	.32	.26	-.02	.0	-.35	.10	10.5	10.6	25.5	24.2	25.2	25.6
1030	0.76	0.5	.51	.46	-.07	.02	-.09	.03	15.3	16.5	30.5	29.1	28.3	29.2
1130	0.92	0.5	.64	.63	-.12	-.03	-.02	-.09	20.1	20.4	33.1	31.6	30.2	30.8
1230	1.04	0.7	.71	.77	-.17	-.04	.0	.05	24.9	24.3	33.7	32.6	30.2	31.7
1330	1.08	0.9	.78	.85	-.16	-.04	.0	.04	26.3	26.9	33.7	33.1	30.8	31.3
1430	1.05	1.1	.77	.82	-.16	-.05	-.01	.06	27.5	29.5	33.6	33.2	31.1	32.3
1530	0.96	0.9	.71	.72	-.17	-.06	-.03	-.03	28.8	31.9	33.8	33.6	30.4	32.5
1630	0.79	0.7	.57	.56	-.13	-.05	-.03	-.08	28.2	29.9	33.9	33.7	30.2	31.3
1730	0.59	0.9	.41	.36	-.10	-.05	-.06	-.24	27.5	27.1	33.1	33.1	29.0	30.2
1830	0.34	1.1	.20	.16	-.07	-.03	-.10	-.19	25.7	23.5	31.7	31.4	27.7	28.6
1930	0.11	0.9	.01	-.02	-.03	-.02	-.25	-.25	17.8	17.0	28.8	28.6	23.8	25.6

Table 11. Mean hourly data used in calculation of ET estimates. Data presented for irrigated and nonirrigated sorghum, August 29, 1972, Redfield, S. D.

Mean time (CDT)	Incoming shortwave radiation (ly/min)	Wind speed (m/sec)	Net radiation (ly/min)		Soil heat flux (ly/min)		Bowen ratio		Vapor pressure deficit (mb)		Air temp at 180 cm elev (Deg C)		Canopy temp (Deg C)	
			Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir
0830	0.31	1.3	.11	.08	.03	.0	-.41	.0	5.1	4.2	21.6	20.9	23.6	24.2
0930	0.55	2.0	.35	.30	-.01	.0	-.30	.13	9.4	8.9	25.6	24.5	26.5	26.5
1030	0.75	1.8	.53	.51	-.05	-.01	.03	.04	14.1	13.6	29.1	28.1	28.8	28.6
1130	0.92	2.2	.68	.68	-.10	-.03	.03	.05	18.7	18.3	31.5	30.5	30.8	30.8
1230	1.04	2.2	.79	.80	-.15	-.04	.05	.02	23.6	22.8	32.9	32.3	31.3	32.1
1330	1.09	2.7	.83	.86	-.14	-.05	.05	.03	25.2	24.9	33.2	32.9	31.1	32.1
1430	1.06	2.7	.82	.84	-.13	-.05	.02	.0	26.8	26.9	33.1	33.0	31.3	32.7
1530	0.89	2.9	.71	.71	-.13	-.05	.03	.0	27.7	27.6	33.0	33.0	30.8	32.3
1630	0.78	2.7	.60	.57	-.08	-.04	.0	-.11	28.2	28.0	33.0	32.9	30.0	31.3
1730	0.60	3.6	.43	.42	-.06	-.04	-.03	-.16	28.9	28.5	32.8	32.7	29.4	30.2
1830	0.32	3.6	.18	.15	-.03	-.03	-.18	-.24	24.2	24.0	31.7	31.5	28.1	29.2
1930	0.10	2.2	-.02	-.04	-.01	-.02	-.29	-.49	18.7	19.4	29.2	29.3	25.9	26.1

Table 12. Mean hourly data used in calculation of ET estimates. Data presented for irrigated and nonirrigated sorghum, August 30, 1972, Redfield, S. D.

Mean time (CDT)	Incoming shortwave radiation (ly/min)	Wind speed (m/sec)	Net radiation (ly/min)		Soil heat flux (ly/min)		Bowen ratio		Vapor pressure deficit (mb)		Air temp at 180 cm elev (Deg C)		Canopy temp (Deg C)	
			Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir	Irri	Nonir
0830	0.08	4.2	.01	.01	.0	.0	-.32	.0	2.0	3.0	23.7	23.6	25.2	25.4
0930	0.19	3.4	.09	.09	-.01	-.01	-.13	.0	6.2	6.8	24.2	24.1	25.2	25.2
1030	0.65	4.5	.47	.45	-.03	-.01	-.08	.21	10.4	10.8	27.1	26.4	27.5	27.9
1130	0.87	4.7	.65	.69	-.07	-.02	-.18	.13	14.6	14.6	29.7	29.1	29.2	30.0
1230	1.02	4.9	.79	.82	-.10	-.03	-.09	.08	17.3	16.6	31.1	30.6	30.2	30.8
1330	1.05	5.4	.81	.81	-.10	-.03	-.04	.48	18.5	17.7	31.2	30.8	30.8	31.3
1430	0.84	4.5	.68	.73	-.11	-.04	.0	.21	19.8	18.7	31.5	31.3	31.1	31.3
1530	0.89	4.7	.71	.73	-.13	-.04	.04	.0	19.6	18.4	31.9	31.9	30.8	32.3
1630	0.71	4.9	.58	.55	-.10	-.04	-.16	-.16	18.5	17.9	32.3	32.0	30.2	31.7
1730	0.53	5.4	.39	.38	-.07	-.04	-.28	-.16	17.5	17.3	31.3	31.0	30.0	30.6
1830	0.15	4.9	.05	.04	-.05	-.03	-.32	-.16	15.6	15.4	29.6	29.5	28.1	28.8
1930	0.08	4.5	.0	-.02	-.02	-.02	-.19	-.32	13.1	13.3	28.3	28.3	27.7	27.7

of nonirrigated data for use in ET estimation. Incoming shortwave radiation and net radiation were measured at an elevation of 2.5 m above the soil surface. Soil heat flux measurements were made at a depth of 5 cm. Wind speed, vapor pressure deficit, and air temperature were measured at an elevation of 180 cm (1 m above the crop surface). Bowen ratios were estimated using temperature and humidity data obtained at the 80 and 180 cm elevations.

Mean hourly data for the irrigated sorghum canopy are presented in Fig. 21, 22, and 23 for three 24-hour periods. The data are presented graphically to illustrate typical diurnal cycles. Data are shown for all hours when measurements were taken. Figures 21 and 23 show the values of incoming shortwave radiation intercepted in the sorghum canopy by a line pyranometer. The radiation instrument was positioned at an elevation of 10 cm in the interrow area of the sorghum canopy. The instrument was alternated daily between the irrigated and nonirrigated sorghum canopies. Results from five days of data for each area indicated that incoming shortwave radiation at the 10 cm elevation was 18% of total incoming shortwave at 2.5 m in the irrigated area, and approximately 23% of total incoming shortwave in the nonirrigated area. The leaf area index of the nonirrigated area (2.8) was less than that of the irrigated area (3.2) allowing more radiation to reach the 10 cm elevation.

Hourly estimates of evapotranspiration rates were made using the methods of van Bavel (1966), energy budget-Bowen ratio, Penman (1948), Bartholic et al. (1970), and Brown and Rosenberg (1972).

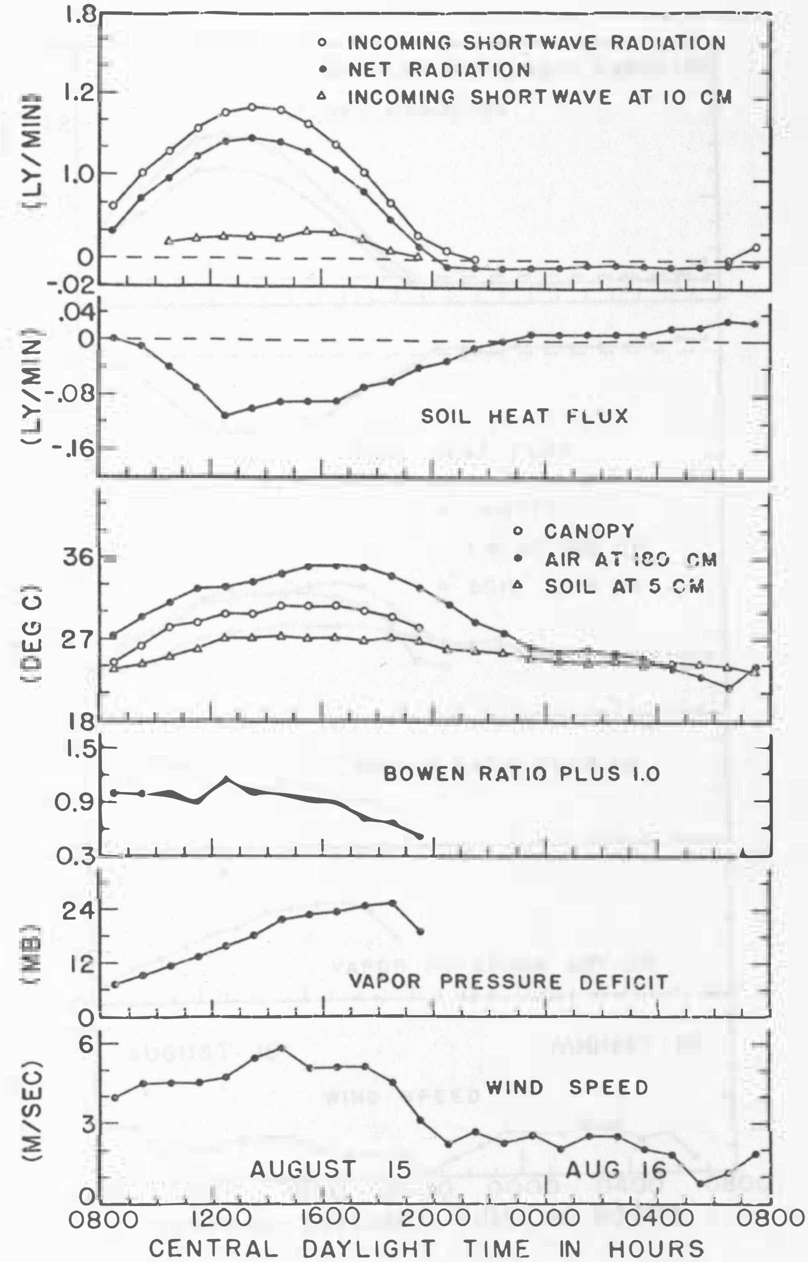

Fig. 21. Mean hourly microclimate data for the irrigated sorghum canopy from 0800 hours CDT August 15 to 0800 hours CDT August 16, 1972.

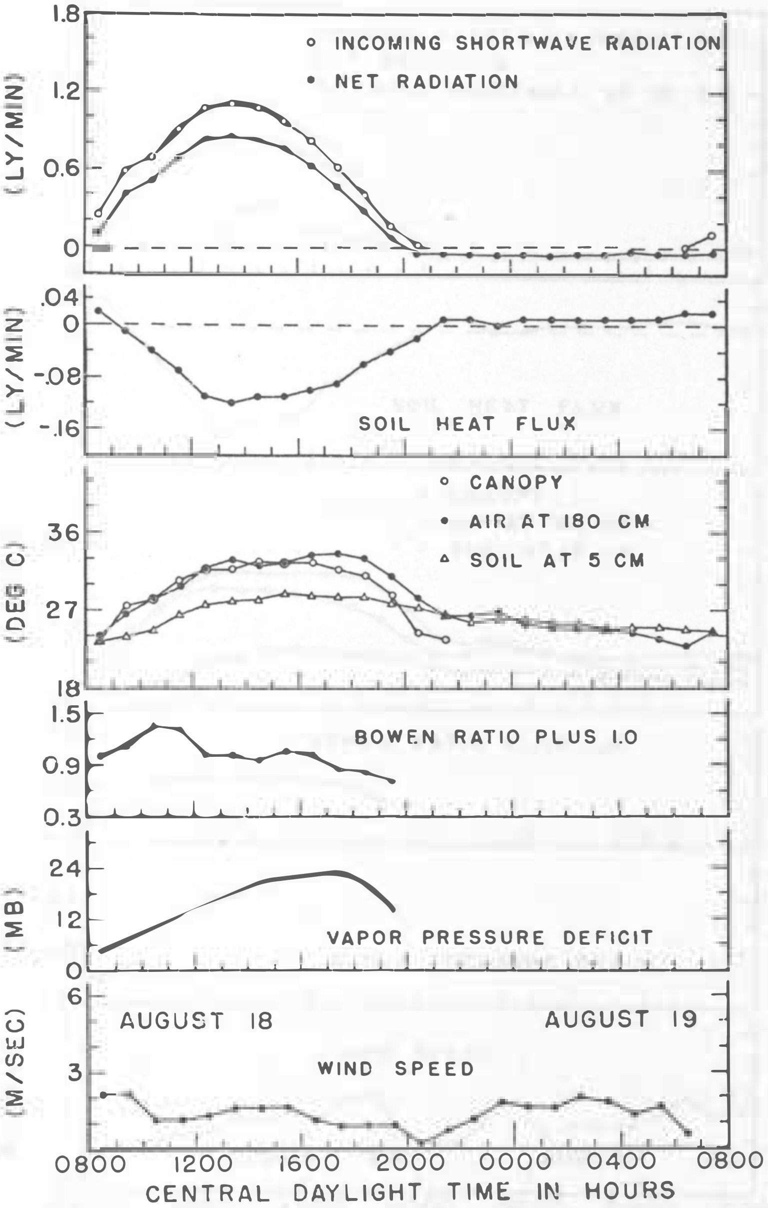

Fig. 22. Mean hourly microclimate data for the irrigated sorghum canopy from 0800 hours CDT August 18 to 0800 hours CDT August 19, 1972.

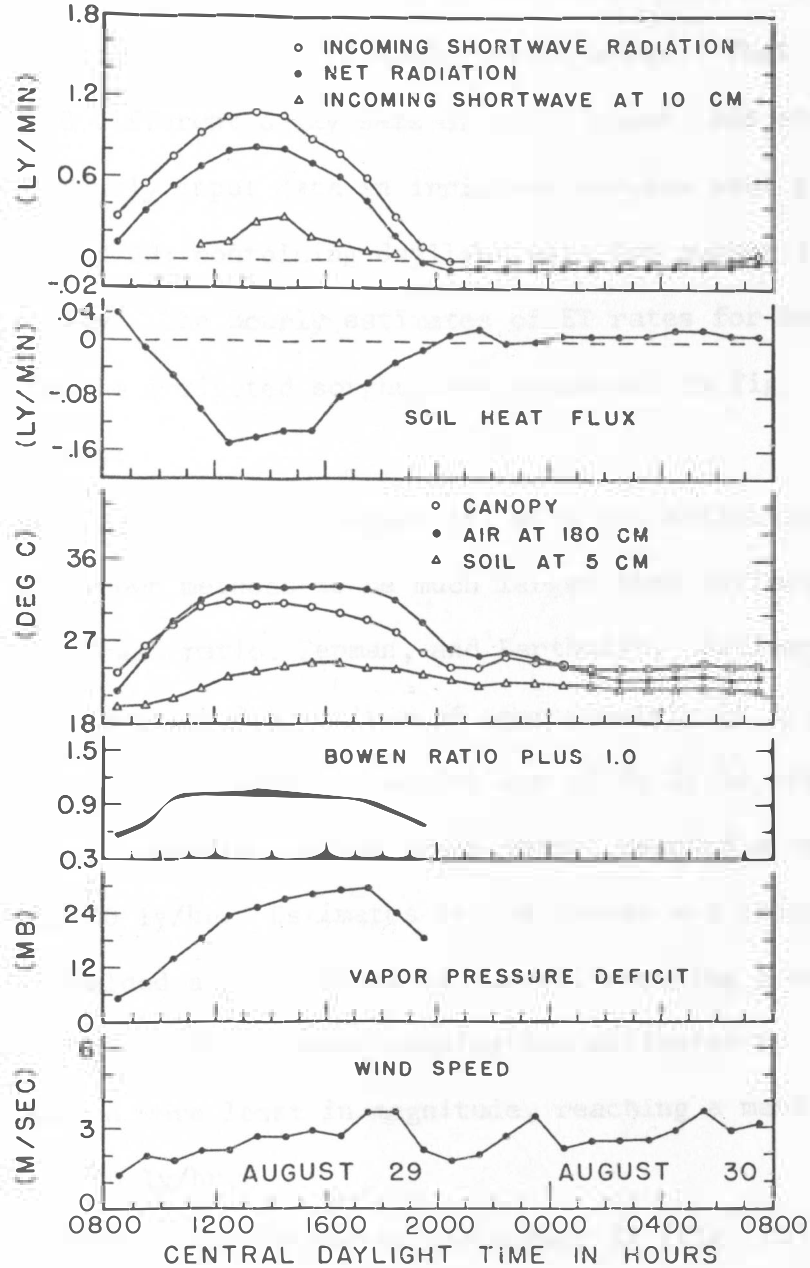

Fig. 23. Mean hourly microclimate data for the irrigated sorghum canopy from 0800 hours CDT August 29 to 0800 hours CDT August 30, 1972.

All input data necessary for use of the five predictive methods are listed in Tables 4 through 12. The ET estimates were made on nine dates in both the irrigated and nonirrigated areas. That yielded essentially 18 different daily sets of soil, plant, and atmospheric conditions. Hourly input data in irrigated sorghum were plotted in Fig. 21, 22, and 23; containing daylight data for August 15, 18, and 29, respectively. The hourly estimates of ET rates for August 15, 18, and 29 in the irrigated sorghum are presented in Fig. 24, 25, and 26, respectively.

The data in Fig. 24 for August 15, show the estimates by the van Bavel and Brown methods to be much larger than estimates by energy budget-Bowen ratio, Penman, and Bartholic. Estimates by the van Bavel method reached a maximum of approximately 95 ly/hr at 1400-1500 CDT. The evaporation equivalent of 58 ly is approximately 1 mm of water. Estimates by the Brown method reached a maximum of approximately 80 ly/hr. Estimates by the Penman and energy budget-Bowen ratio yielded almost identical curves, reaching a maximum of approximately 45 ly/hr. Evapotranspiration estimates by the Bartholic method were least in magnitude, reaching a maximum of approximately 40 ly/hr.

Evapotranspiration estimates for August 18 (Fig. 25) were similar for all equations used. The van Bavel estimates were slightly higher (by 5 ly/hr) in the afternoon, but agreed well at other times. The maximum difference between ET estimates was approximately 15 ly/hr.

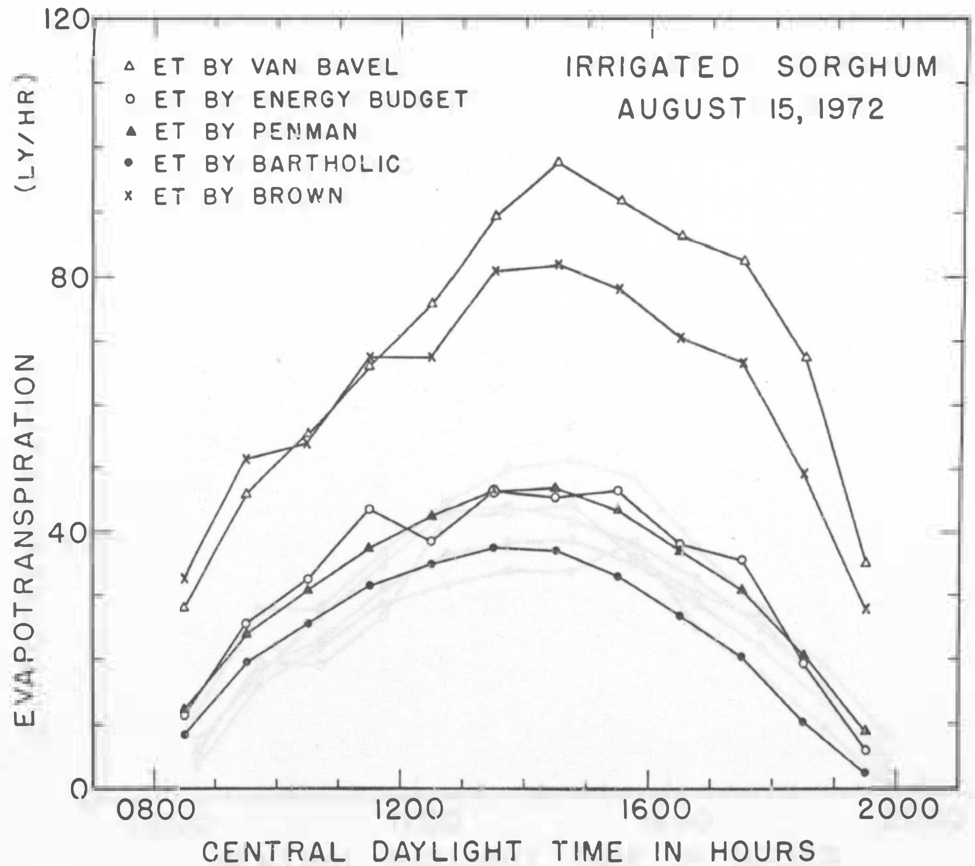

Fig. 24. Hourly estimates of evapotranspiration rates for the irrigated sorghum on August 15, 1972, using the methods of van Bavel, energy budget-Bowen ratio, Penman, Bartholic, and Brown.

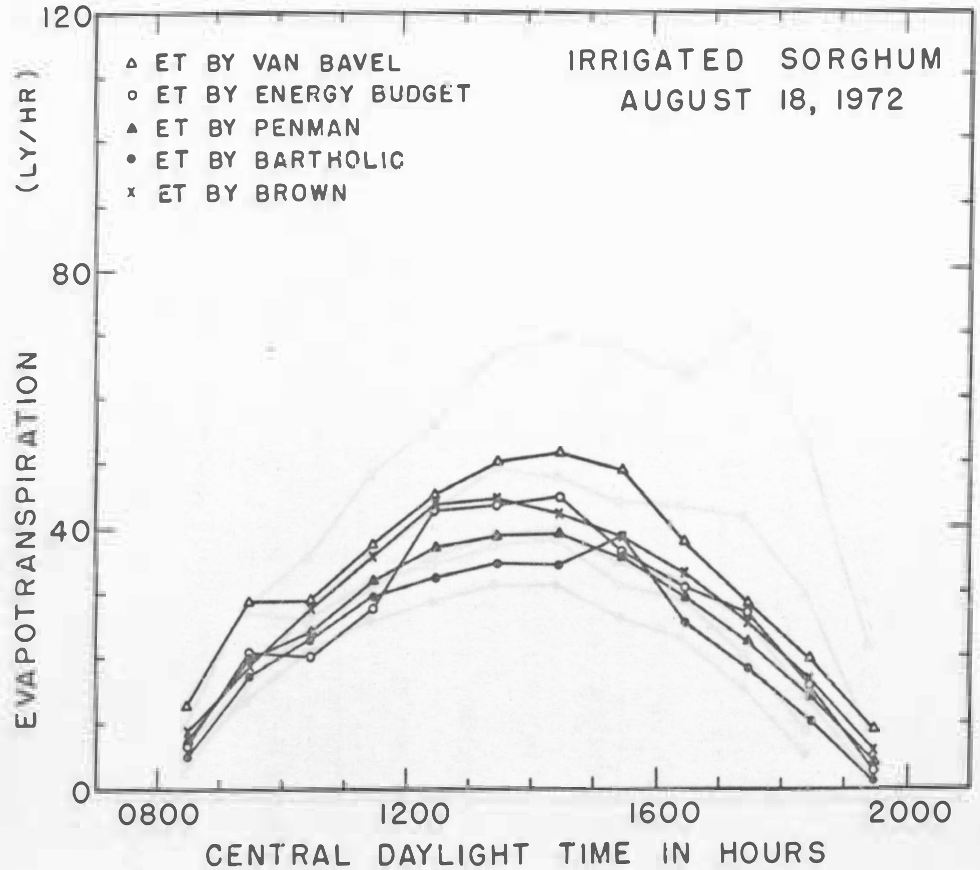

Fig. 25. Hourly estimates of evapotranspiration rates for the irrigated sorghum on August 18, 1972, using the methods of van Bavel, energy budget-Bowen ratio, Penman, Bartholic, and Brown.

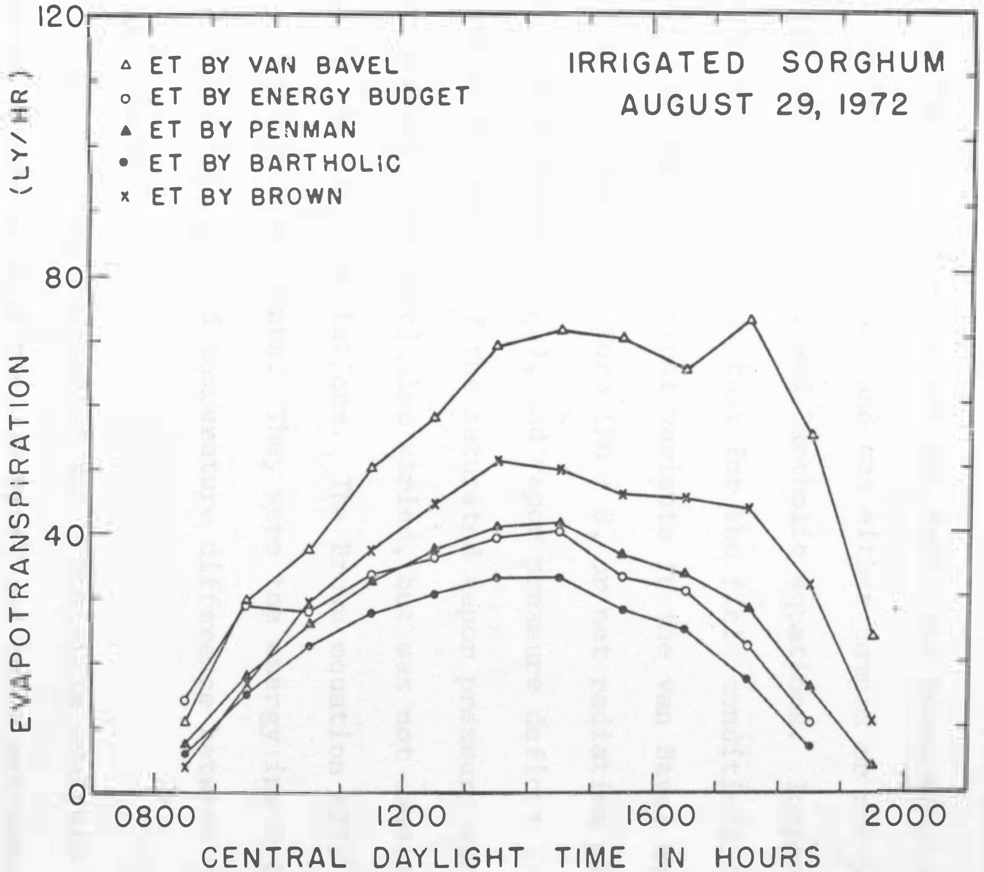

Fig. 26. Hourly estimates of evapotranspiration rates for the irrigated sorghum on August 29, 1972, using the methods of van Bavel, energy budget-Bowen ratio, Penman, Bartholic, and Brown.

The range of ET estimates by the methods of van Bavel and Brown shown in Fig. 26 was intermediate between those of Fig. 24 and 25. Estimates by the methods of energy budget-Bowen ratio, Penman, and Bartholic were similar in magnitude for the three dates. It would appear that some term in the van Bavel and Brown equations caused day to day fluctuations, and was either damped or not present in the energy budget, Penman, and Bartholic equations. Inspection of equation (25) indicates that for the field conditions of this study, there were three principal variants in the van Bavel equation. They were the energy input term (Rn + S, or net radiation plus soil heat flux), wind speed (u_{180}), and vapor pressure deficit (e_{s180} - e_{a180}). The term D/G (slope of the saturated vapor pressure curve over the psychrometric constant) also varied, but was not considered a factor causing the large variations. The Brown equation (27) also contained three principal variants. They were the energy input term (Rn + S), wind speed (u_{180}), and temperature difference between canopy and air (T_{can} - T_{180}).

Simple linear regression and correlation analysis was conducted between the results of the van Bavel and Brown estimates and the input terms of each equation. The cumulative ET estimate for each day (cm/day) was compared against the mean value of the input variables for that day. With nine days of data and two water regimes, there were 18 observations for each analysis.

The results of the statistical analysis for the van Bavel estimates of ET are presented in Fig. 27. Only 4% of the total

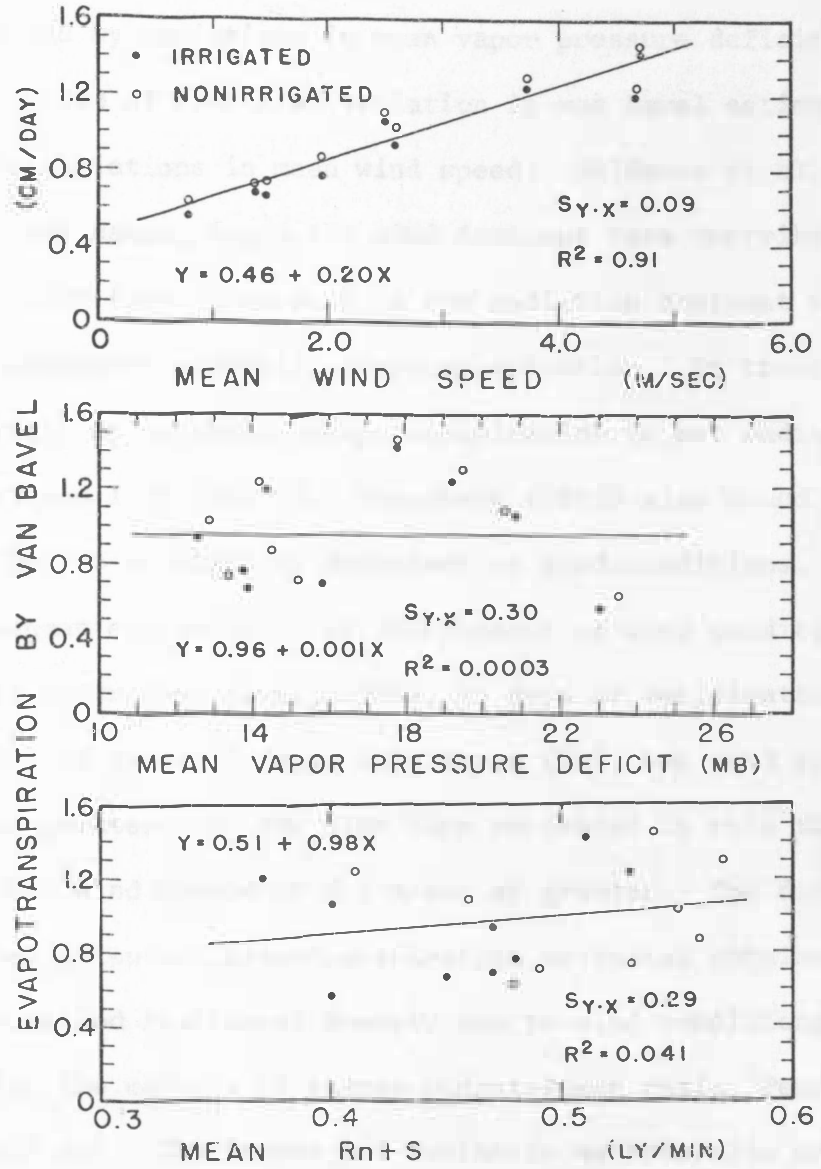

Fig. 27. Comparison of ET by van Bavel estimates in cm/day to the daily mean of the hourly input data used in the van Bavel equation; where Rn + S is net radiation plus soil heat flux at the 5 cm depth and the vapor pressure deficit and wind speed were measured at the 180 cm elevation.

variation is explained by variations in mean Rn + S, and less than 1% is explained by variations in mean vapor pressure deficit. Approximately 91% of the total variation in van Bavel estimates is explained by variations in mean wind speed. Skidmore et al. (1969), using two study dates, found the wind dominant term contributed 33 (day 1) and 113% (day 2) as much as the radiation dominant term to the total calculated potential evapotranspiration. On those two days, the ratio of potential evapotranspiration to net radiation was 0.98 (day 1) and 1.60 (day 2). Rosenberg (1969) also found van Bavel's method to be strongly dependent on wind conditions. He also found the Penman estimates to be independent of wind conditions. In the original paper (van Bavel, 1966), 13 days of verification data were listed. Of those 13 days, only three (23%) had wind speeds of 2.0 m/sec or greater. Of the nine days presented in this thesis, five (56%) had wind speeds of 2.0 m/sec or greater. The data clearly indicate that potential evapotranspiration estimates obtained using van Bavel's method fluctuated sharply due to wind conditions, while results using the methods of energy budget-Bowen ratio, Penman, and Bartholic did not. The Penman and Bartholic methods also estimate potential evapotranspiration, while the energy budget-Bowen ratio method estimates actual evapotranspiration. Considering the wind nature of the Great Plains, caution should be used if potential ET estimates obtained using van Bavel's method are related to actual ET.

Figure 28 presents the results of the simple linear regression and correlation analysis applied to estimates of ET obtained using

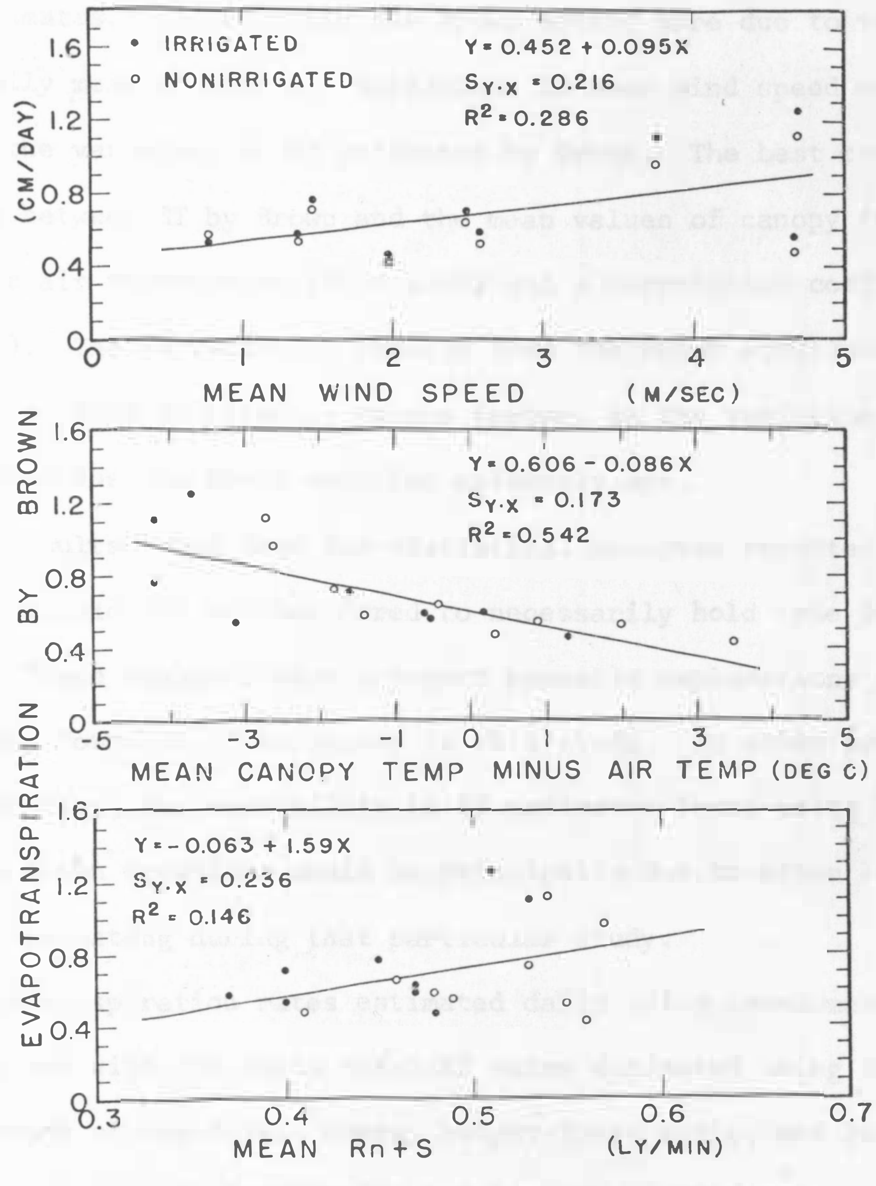

Fig. 28. Comparison of ET by Brown estimates in cm/ day to the daily mean of the hourly input data used in the Brown equation; where Rn + S is net radiation plus soil heat flux at the 5 cm depth and air temperature and wind speed were measured at the 180 cm elevation.

the Brown method. Results indicate that 14.6% of the total variation in ET estimates obtained using the Brown method were due to variations in the daily mean of Rn + S. Variations in mean wind speed explained 28.6% of the variation in ET estimates by Brown. The best correlation was found between ET by Brown and the mean values of canopy temperature minus air temperature (R^2 = 0.542 and a correlation coefficient of -0.736). The variation in results from the Brown equation do not appear to be tied as strongly to one factor, as the variation in results from the van Bavel equation evidently are.

The results found from the statistical analyses reported in Fig. 27 and 28 should not be considered to necessarily hold true in other studies. These analyses merely report probable explanations for the variability found in ET estimates in this study. In other areas, or at another time, the variability in ET estimates found using the van Bavel and Brown equations could be principally due to other input factors fluctuating during that particular study.

Evapotranspiration rates estimated daily using tensiometer data were compared with the daily total ET rates estimated using the well-known methods of van Bavel, energy budget-Bowen ratio, and Penman. Evapotranspiration by tensiometer results are plotted versus results from each of the three equations in Fig. 29. The ET by van Bavel estimates are much larger than ET by tensiometer estimates. The van Bavel method estimates potential evapotranspiration and the tensiometer method estimates actual ET, so the van Bavel estimates would have been expected to be larger. The van Bavel method has been

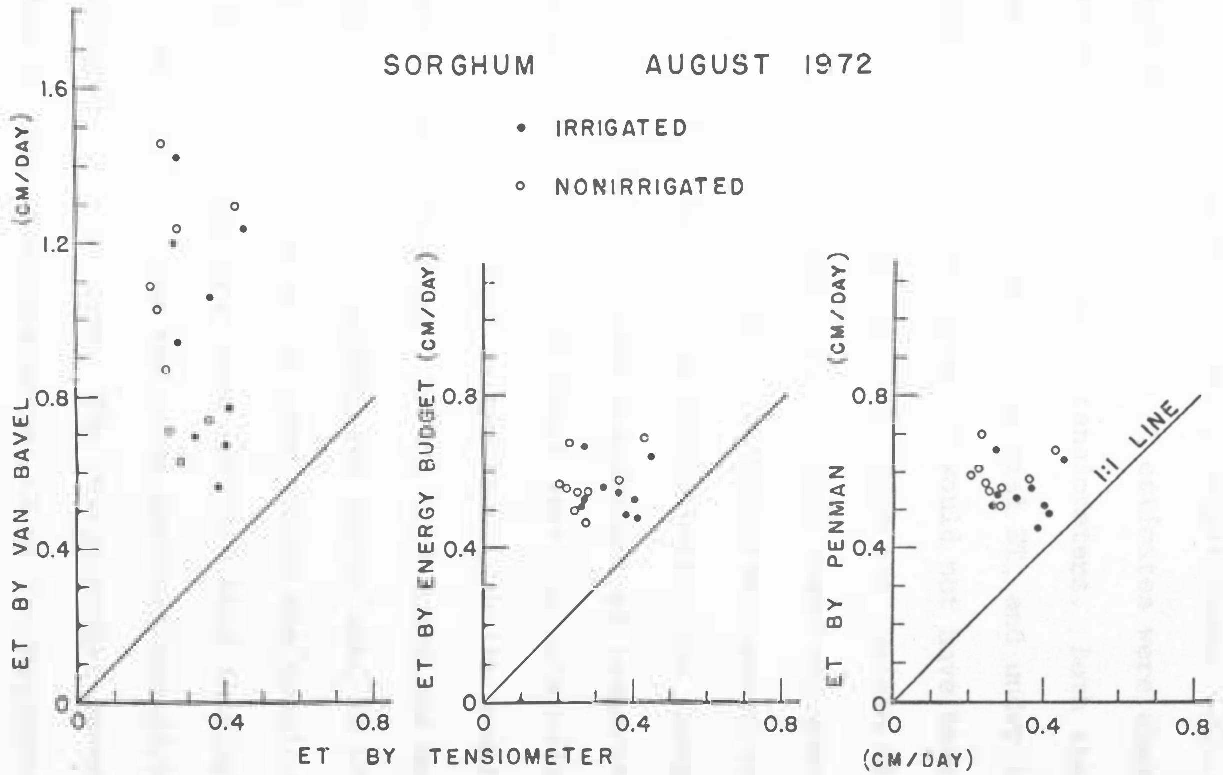

Fig. 29. Comparison of ET estimated using tensiometer data to ET estimated using the methods of van Bavel, energy budget-Bowen ratio, and Penman. Daily estimates using the three microclimate equations were found by summing the calculated hourly estimates.

shown to be highly affected by wind speed, with wind speed probably causing most of the variations shown in Fig. 29.

Results from the energy budget-Bowen ratio and Penman methods were very similar. Their ET estimates were always greater than ET estimates obtained using tensiometers. Both the Penman and van Bavel methods estimate potential ET, and under the conditions of this study, actual tensiometer ET would not have been expected to equal potential ET. However, that does not explain why energy budget-Bowen ratio estimates were larger than tensiometer estimates. It is difficult to say which method (tensiometer or energy budget-Bowen ratio) is in error, or possibly both. The energy budget-Bowen ratio method requires accurate measurement of temperature and vapor pressure gradients over short vertical intervals. The differences over the short intervals are usually quite small, requiring considerable accuracy. In the derivation and use of the energy budget-Bowen ratio method, the energy used in photosynthesis and the energy stored in the crop volume are considered negligible and neglected. However, Lemon (1960) stated that approximately 8% of net radiation for the total daylight period was being used in photosynthesis by corn. The energy budget-Bowen ratio method would then be overestimating actual ET by the neglected amount divided by (1 + B). Literature reports on comparison of ET by energy budget-Bowen ratio to ET by lysimeter varies. Rosenberg (1969) found lysimeter estimates of ET to be greater than energy budget-Bowen ratio estimates of ET. Pruitt and Lourence (1968) found daily ET estimated using the energy budget-Bowen ratio method to be from 1 to 20% larger than ET measured using a lysimeter. The use of tensiometers appears to be sound physically with two main possible sources of error. They are the soil water desorption curves and the hydraulic conductivity relationships. The desorption curve results have been compared in the field to results obtained using neutron scattering, with good agreement found (Stone et al., 1973a). With the desorption curves being correct, the estimates of profile water depletion should have been accurate. The flux measurements, which use the hydraulic conductivity relationships, appear to have been correct. During the study, flux was upward in the nonirrigated area and downward in the irrigated area. An error in the hydraulic conductivity relationships would have produced errors in the flux values. With the flux being added to depletion in one case (nonirrigated) and subtracted in the other (irrigated), the good agreement between ET estimates shown in Fig. 12 would have been difficult to obtain if an error had existed.

Data similar to that presented in Fig. 29 are presented in Fig. 30. In Fig. 30, ET estimates found using tensiometer data are compared to daily estimates of ET found using the Brown and Bartholic methods. The Brown and Bartholic methods make use of the canopy temperature in estimating ET. The Brown estimates are greater and fluctuate much more than do the Bartholic estimates. Analysis of the daily fluctuations in ET estimated using the Brown method was presented in Fig. 28. The Bartholic estimates showed better

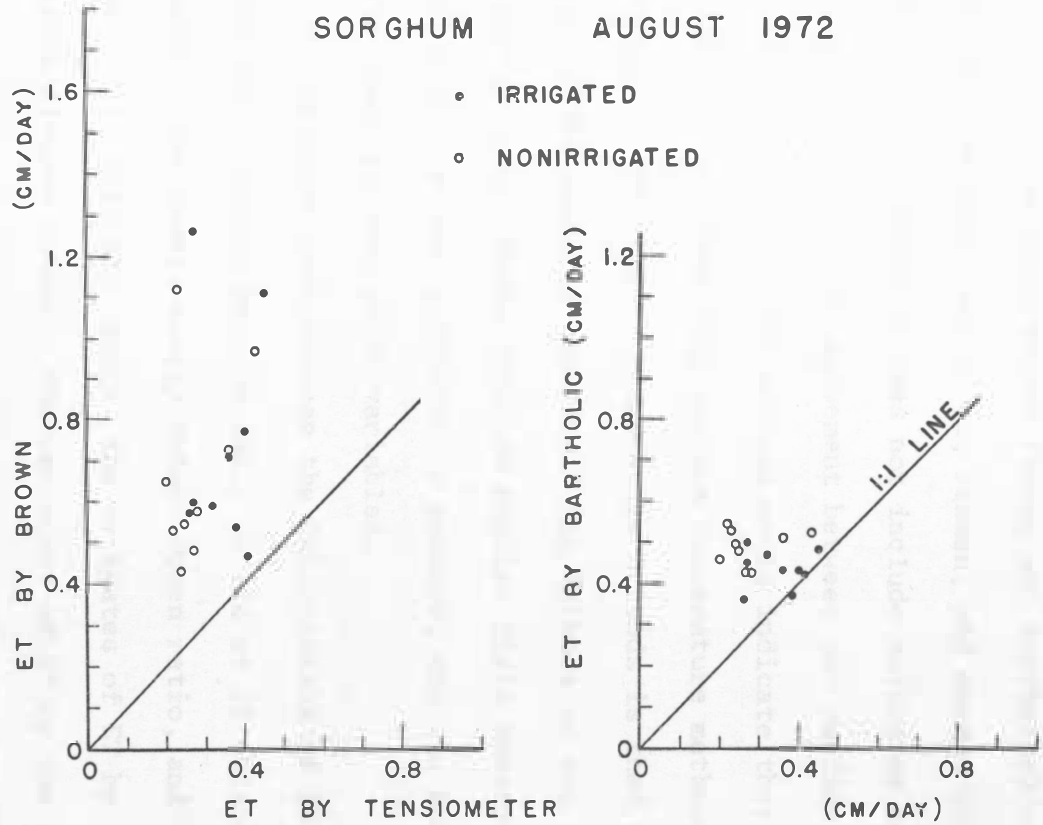

Fig. 30. Comparison of ET estimated using tensiometer data to ET estimated using the methods presented by Brown and Bartholic. The daily Brown and Bartholic estimates were found by totaling the calculated hourly estimates.

agreement with tensiometer estimates than did any of the other four microclimate methods.

A major objective of this thesis was to evaluate the two methods that use surface temperatures (Brown and Bartholic) against the more established methods (van Bavel, Penman, and energy budget-Bowen ratio). This evaluation does not include estimates made using tensiometer data. Good agreement between the surface temperature and standard microclimate methods would indicate that use could be made of the less demanding surface temperature methods. The main advantage of the surface temperature methods is that they do not require field measured humidity. The methods of van Bavel, Penman, and energy budget-Bowen ratio do require field measured humidity. Humidity is the most difficult to measure, and the most unreliable, of the commonly used input variables.

A comparison made between the daily totals of ET obtained by the Bartholic method and the daily totals of ET obtained by the methods of van Bavel, energy budget-Bowen ratio, and Penman is presented in Fig. 31. Again, the estimates of ET by van Bavel show a highly diverse nature. The estimates of ET by the energy budget-Bowen ratio and Penman methods are consistently higher than ET estimated using the Bartholic method. The mean daily estimate of ET by Penman was 0.57 cm/day, of ET by energy budget-Bowen ratio was 0.56 cm/day, and of ET by Bartholic was 0.46 cm/day.

A comparison similar to that presented in Fig. 31 is presented in Fig. 32. In Fig. 32, daily totals of ET estimated using the

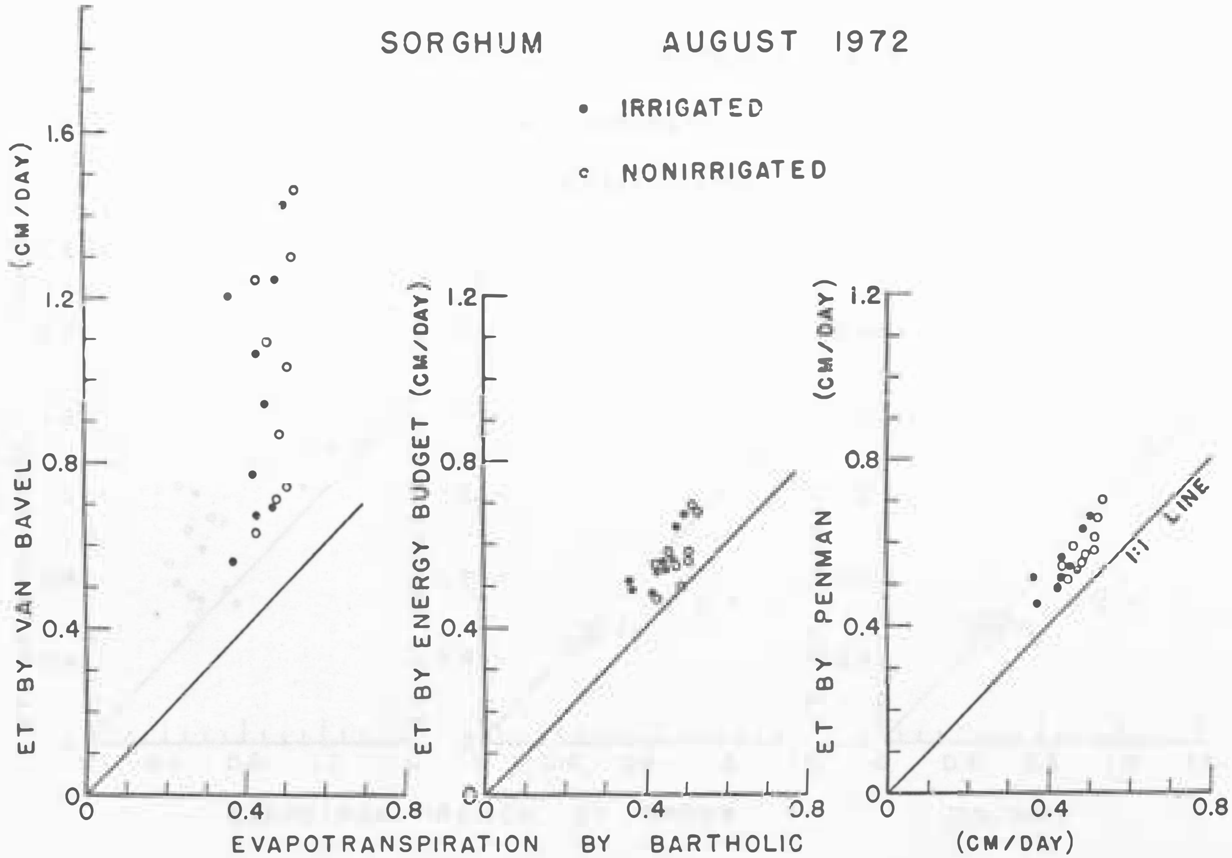

Fig. 31. Comparison of ET estimated using the Bartholic method to ET estimated using the methods of van Bavel, energy budget-Bowen ratio, and Penman. Data presented are the daily totals of the hourly estimates.

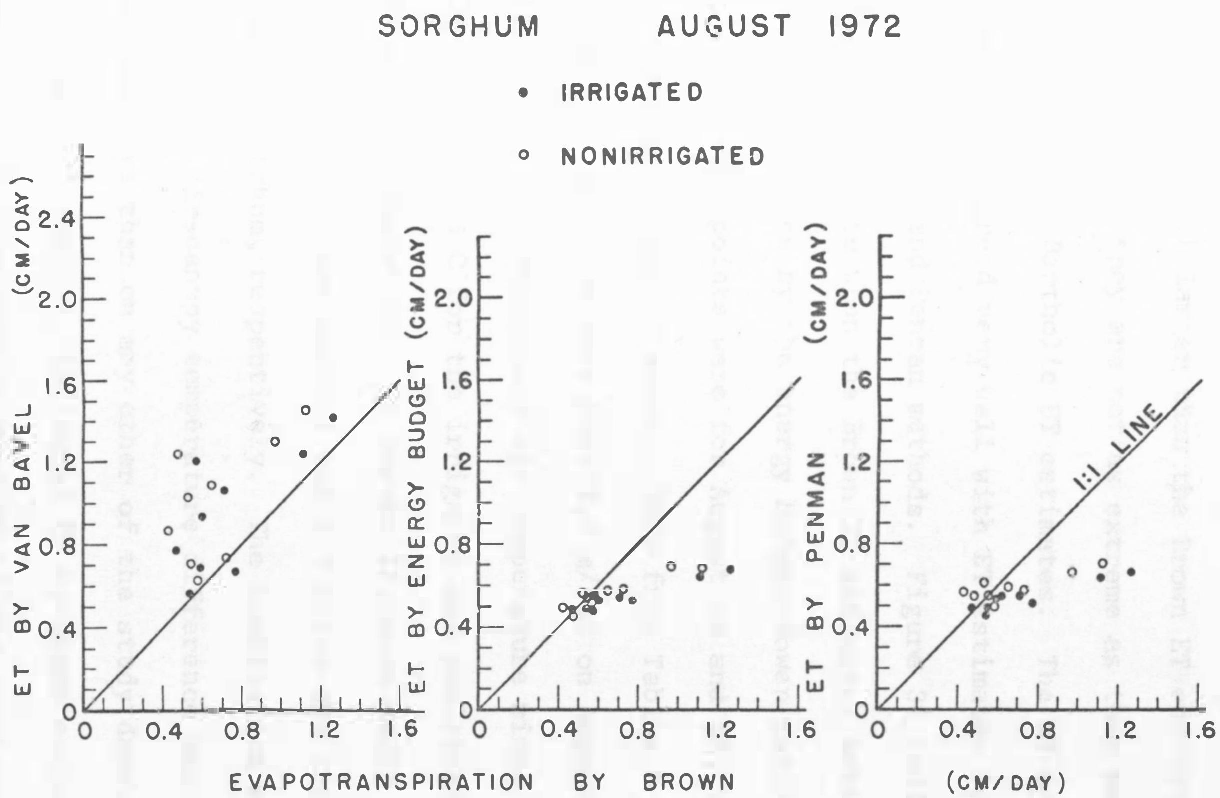

Fig. 32. Comparison of ET estimated using the Brown method to ET estimated using the methods of van Bavel, energy budget-Bowen ratio, and Penman. Data presented are the daily totals of the hourly estimates.

Brown method are presented versus ET estimates made using the van Bavel, Penman, and energy budget-Bowen ratio methods. The van Bavel ET estimates are much larger than the Brown ET estimates and show a diverse nature, but they are not as extreme as they were in the comparison with the Bartholic ET estimates. The ET estimates by the Brown method agreed very well with ET estimates by the energy budget-Bowen ratio and Penman methods. Figure 32 indicates there were four data points when the Brown ET estimates were much higher than the ET estimates by the energy budget-Bowen ratio and Penman methods. The four points were for August 14 and 15, in both the irrigated and nonirrigated areas. Data from Tables 5 and 6 show mean daily wind speed to have been 3.7 m/sec on August 14 and 4.7 m/sec on August 15. Mean daily air temperature minus canopy temperature was 4.2 and 2.6 C for the irrigated and nonirrigated sorghum, respectively, on August 14. On August 15, mean daily air temperature minus canopy temperature was 3.7 and 2.7 C for the irrigated and nonirrigated sorghum, respectively. The combination of high wind speed and large air-canopy temperature difference was more evident on those two days than on any other of the study days. Figure 28, and its associated discussion, indicated ET by Brown estimates to be dependent upon fluctuations in wind speed and air-canopy temperature differences. If results from August 14 and 15 are included, the mean daily ET estimate by Brown was 0.70 cm/day. If those two dates are not included, the mean daily ET estimate was 0.58 cm/day. This is very similar to the Penman mean (0.57 cm/day) and to the energy budget-Bowen ratio mean (0.56 cm/day).

Evapotranspiration rates were estimated using approximately 100 hours of data collected from each of the sorghum areas. Simple linear regression and correlation analyses were performed using the 100 hours of data from each area. The statistical results from the irrigated and nonirrigated areas were very similar, so the estimates from each area were pooled yielding approximately 200 observations for use in the reported statistical analyses. The results from the analyses are presented in Table 13. Evapotranspiration values listed in Table 13 are in units of ly/hr.

Regression equations are listed with the ET estimates by Bartholic (ETBA) and Brown (ETBR) as the dependent variables. Evapotranspiration estimates by energy budget-Bowen ratio (ETEB), van Bavel (ETVB), and Penman (ETPN) are the independent variables. Values of standard error (SE) of the estimate indicate less scatter in the Bartholic ET estimates (ETBA), than in the Brown ET estimates (ETBR). The lower the value of SE of the estimate, the less the scatter of data about the regression line. If N (number of observations) is large enough, 68% of the observations should lie within lines constructed parallel to the regression line at a vertical distance of ± SE. The ETBA versus ETEB data had a SE of the estimate of 3.89 ly/hr and the ETBA versus ETPN data had a SE of the estimate value of 2.70 ly/hr. The SE of the estimate value for the ETBA versus ETVB data was the largest of the three at 8.69 ly/hr.

Table 13. Simple linear regression and correlation analysis of ET by Bartholic (ETBA) and ET by Brown (ETBR) with ET by energy budget-Bowen ratio (ETEB), ET by van Bavel (ETVB), and ET by Penman (ETPN). ET values are in units of ly/hr.

Regression equation	Number of observations	SE of the estimate	Correlation** coefficient	Coefficient of determination
ETBA = -0.20 + 0.817ETEB	197	3.89	0.944	0.892
ETBA = 5.90 + 0.356ETVB	204	8.69	0.697	0.485
ETBA = -2.68 + 0.91ETPN	204	2.70	0.975	0.950
ETBR = 5.09 + 1.07ETEB	190	11.06	0.783	0.613
ETBR = 3.44 + .655ETVB	202	10.76	0.817	0.667
ETBR = 1.31 + 1.21ETPN	202	10.23	0.836	0.699

**All values significant at the 0.01 probability level.

The SE of the estimate values involving the Brown method were all of approximately the same magnitude (10-11 ly/hr).

All six of the correlations were significant at the 0.01 probability level. The coefficient of determination values (ratio of explained variation to total variation denoted by R^2) show the ETBA versus ETVB correlation having the most unexplained variation ($R^2 = 0.485$). The coefficient of determination values for ETBA versus ETEB and for ETBA versus ETPN were very good; 0.892 and 0.950, respectively. All coefficient of determination values involving ETBR were between 0.6 and 0.7.

The simple linear regression equations listed in Table 13 are shown in Fig. 33. A 1:1 line was drawn to aid in evaluation of the various methods. The van Bavel method agreed poorly with both the Bartholic and Brown methods, as evidenced by the distance from the ETVB regression line to the 1:1 line. The agreement between the ETPN and ETEB regression lines and the 1:1 line was about equal in each comparison. The regression lines were below the 1:1 line in the ETBA case and above the 1:1 line in the ETBR case. If the independent variables ETPN, ETEB, and ETVB all assume a typical afternoon value of 40 ly/hr (see Fig. 24, 25, and 26), the ETBA estimates would be 33.7, 32.5, and 20.2 ly/hr, respectively. The ETBA estimates are too low by 15.7, 18.8, and 49.5%, respectively, if the value of 40 ly/hr for each of the independent variables is assumed correct. If ETPN, ETEB, and ETVB assume a value of 40 ly/hr, the ETBR estimates are 49.7, 47.9, and 29.6 ly/hr, respectively. The

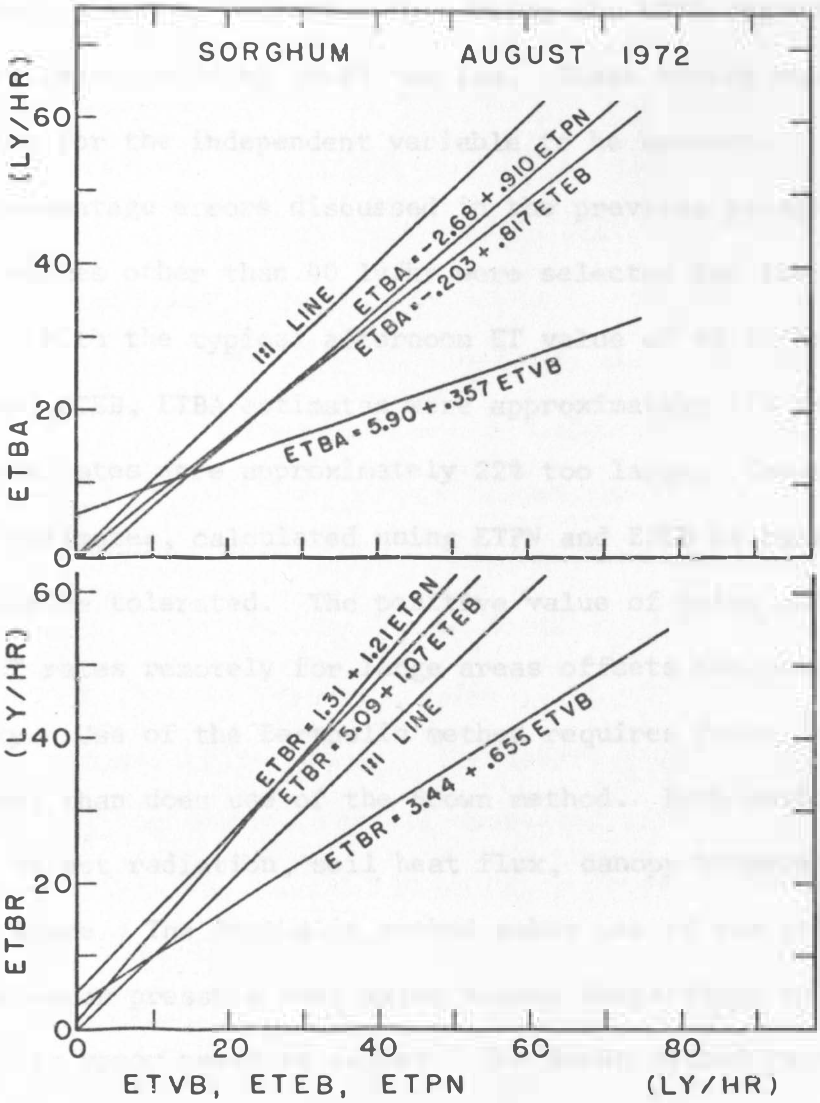

Fig. 33. Plot of linear regression equations where ET by Bartholic (ETBA) and ET by Brown (ETBR) are dependent variables and ET by energy budget-Bowen ratio (ETEB), ET by van Bavel (ETVB), and ET by Penman (ETPN) are the independent variables.

ETBR estimates would be too high by 24.2 and 19.7% using the ETPN and ETEB regression lines, respectively. Using the ETVB regression line, the ETBR estimate would be 26.0% too low. These errors would assume the 40 ly/hr for the independent variable to be correct.

The percentage errors discussed in the previous paragraph would change if values other than 40 ly/hr were selected for the independent variables. With the typical afternoon ET value of 40 ly/hr assumed for ETPN and ETEB, ETBA estimates were approximately 17% too small and ETBR estimates were approximately 22% too large. The error of 20% in ET estimates, calculated using ETPN and ETEB as base values, can possibly be tolerated. The positive value of being able to estimate ET rates remotely for large areas offsets the possible loss in accuracy. Use of the Bartholic method requires fewer input measurements than does use of the Brown method. Both methods use estimates of net radiation, soil heat flux, canopy temperature, and air temperature. The Bartholic method makes use of the published saturation vapor pressure over water versus temperature relationship for obtaining vapor pressure values. The Brown method requires an estimate of wind speed and aerodynamic characteristics of the evaporating surface (zero plane displacement and roughness length). The Brown method does require field data in addition to that needed by the Bartholic method, thus making the Bartholic method more desirable when considering necessary input.

SUMMARY AND CONCLUSIONS

A study was conducted to investigate the transfer of energy and water in the soil-plant-atmosphere continuum of irrigated and nonirrigated sorghum. Tensiometer data were used to estimate soil water flux and evapotranspiration rates in each area. Five equations using microclimate data were also employed to estimate evapotranspiration rates. Three of the equations were the well-known methods of van Bavel, Penman, and energy budget-Bowen ratio. The other two equations used the surface temperature of the evaporating surface in estimating ET, and have recently been discussed by Bartholic et al. (1970) and Brown and Rosenberg (1972).

Soil water flux in the nonirrigated area was upward in all soil depth intervals during the study. The upward flux in the 15-30, 30-50, and 50-70 cm depth intervals decreased with time during the study. Upward flux in the 130-150 cm depth interval reached a maximum of -0.17 cm/day and then remained near -0.11 cm/day during the final two weeks of the study. Immediately after irrigation, flux was downward in all soil depth intervals in the irrigated sorghum. The flux in the 130-150 cm depth interval remained downward throughout the study. The flux in the 15-30, 30-50, and 50-70 cm depth intervals reversed and became upward within one week following irrigation. Evapotranspiration rates were estimated as profile water depletion minus soil water flux at the 150 cm depth. If profile water depletion had been equated with evapotranspiration, and flux neglected, ET would have been overestimated in the irrigated sorghum and underestimated in the nonirrigated sorghum.

The leaf diffusion resistance (LDR) data indicated a gradual increase in stress in the nonirrigated sorghum relative to the irrigated sorghum during the study. Differences between LDR measurements of irrigated and nonirrigated sorghum followed the same general pattern as the differences in ET rates between the two water regimes. The relationship between LDR differences and ET differences was evident even though severe stress did not develop during the study.

Canopy temperature data indicated that the irrigated sorghum canopy was usually 1-3 C cooler than the nonirrigated canopy during daylight hours. During nighttime, there was no clear temperature difference between the irrigated and nonirrigated sorghum canopies. On most dates, the air temperature was warmer than the canopy temperature, often by as much as 3-5 C. During early morning hours, 0000 to 0800 hours CDT, the canopy temperature was usually warmer than air temperature, often by 5-6 C. Canopy temperature responded rapidly to changes in global radiation, with the air temperature remaining at a near constant value. The canopy response was more rapid and complete when radiation increased than when it decreased.

The five equations using microclimate data to estimate ET gave larger estimates of ET than did the tensiometer data. The van Bavel, Penman, and Bartholic methods are developed to yield estimates of potential ET. During the thesis study, actual ET would have been less than potential and the smaller estimates of ET obtained using tensiometers would have been expected. The energy budget-Bowen ratio method neglects some energy sinks which would have caused its estimates of ET to be larger than actual ET.

With the development of remote thermal scanners, there is increasing interest in using the temperature of the evaporating surface to estimate evaporation. Both the Bartholic and Brown methods make use of canopy temperatures in their estimation of evapotranspiration rates. Using simple linear regression and correlation analysis, the Bartholic ET estimates were found to be approximately 17% smaller than typical ET estimates by the Penman and energy budget-Bowen ratio methods. Using the same analysis, the Brown method yielded ET rates approximately 22% larger than typical Penman and energy budget-Bowen ratio estimates of ET rates. Both methods appear useable in remotely determining ET rates of vegetated surfaces. The Bartholic method requires less input data than does the Brown method. Thus, the Bartholic method is slightly more desirable from the standpoint of accuracy and input data.

LITERATURE CITED

Aston, A. R., and C. H. van Bavel. 1972. Soil surface water depletion and leaf temperature. Agron. J. 64:368-373.

Barger, G. L., T. L. Noffsinger, J. J. Rahn, and W. C. Palmer. 1970. ESSA: A disseminator and user of ET data. p. 1-6. In Evapotranspiration in the Great Plains. Great Plains Agricultural Council, Publication No. 50, Kansas State University, Manhattan.

Bartholic, J. F., L. N. Namken, and C. L. Wiegand. 1970. Combination equations used to calculate evaporation and potential evaporation. ARS, USDA 41-170.

Bartholic, J. F., L. N. Namken, and C. L. Wiegand. 1972. Aerial thermal scanner to determine temperatures of soils and of crop canopies differing in water stress. Agron. J. 64:603-608.

Black, T. A., W. R. Gardner, and C. B. Tanner. 1970. Water storage and drainage under a row crop on a sandy soil. Agron. J. 62:48-51.

Bowen, I. S. 1926. The ratio of heat losses by conduction and by evaporation from any water surface. Physical Review 27:779-787.

Brown, K. W., and N. J. Rosenberg. 1970. Effect of windbreaks and soil water potential on stomatal diffusion resistance and photosynthetic rate of sugar beets (Beta vulgaris). Agron. J. 62:4-8.

Brown, K. W., and N. J. Rosenberg. 1971. Energy and CO_2 balance of an irrigated sugar beet (Beta vulgaris) field in the Great Plains. Agron. J. 63:207-213.

Brown, K. W., and N. J. Rosenberg. 1972. A resistance model to predict evapotranspiration and its application to a sugar beet field. p. 5.1-5.31. In Research in evapotranspiration 1969-1972. Horticulture Progress Report No. 96, University of Nebraska, Lincoln.

Buettner, K. J. K., and C. D. Kern. 1965. The determination of infrared emissivities of terrestrial surfaces. J. Geophys. Res. 70:1329-1337.

Carlson, C. G. 1972. Grain sorghum canopy temperature as a function of meteorological conditions. Unpublished M. S. Thesis. South Dakota State University, Brookings.

Cassel, D. K. 1971. Water and solute movement in Svea loam for two water management regimes. Soil Sci. Soc. Amer. Proc. 35:859-866.

Conaway, J., and C. H. M. van Bavel. 1967a. Evaporation from a wet soil surface calculated from radiometrically determined surface temperatures. J. Appl. Meteor. 6:650-655.

Conaway, J., and C. H. M. van Bavel. 1967b. Radiometric surface temperature measurements and fluctuations in sky radiant emmittance in the 600 to 1300 cm^{-1} waveband. Agron. J. 59:389-390.

Doering, E. J., R. C. Reeve, and K. R. Stockinger. 1964. Salt accumulation and salt distribution as an indicator of evaporation from fallow soils. Soil Sci. 97:312-319.

Drake, B. G., K. Raschke, F. B. Salisbury. 1970. Temperatures and transpiration resistances of Xanthium leaves as affected by air temperature, humidity, and wind speed. Plant Physiol. 46:324-330.

Ehrler, W. L., and C. H. M. van Bavel. 1967. Sorghum foliar responses to changes in soil water content. Agron. J. 59:243-246.

Ehrler, W. L., and C. H. M. van Bavel. 1968. Leaf diffusion resistance, illuminance, and transpiration. Plant Physiol. 43:208-214.

Fritschen, L. J. 1965. Miniature net radiometer improvements. J. Appl. Meteor. 4:528-532.

Fuchs, M., and C. B. Tanner. 1966. Infrared thermometry of vegetation. Agron. J. 58:597-601.

Goltz, S. M., C. B. Tanner, A. A. Millar, and A. R. G. Lang. 1971. Water balance of seed onion field. Agron. J. 63:762-765.

Hanks, R. J., H. R. Gardner, and R. L. Florian. 1968. Evapotranspiration-climate relations for several crops in the Central Great Plains. Agron. J. 60:538-542.

Hanks, R. J., H. S. Jacobs, H. E. Schimmelpfennig, and M. Nimah. 1971. Evapotranspiration of oats as estimated by the energy budget, aerodynamic, and combination methods. Utah Resource Series 53, Agr. Exp. Sta., Utah State Univ.

Hanks, R. J., and R. W. Shawcroft. 1965. An economical lysimeter for evapotranspiration studies. Agron. J. 57:634-636.

Hillel, D. 1971. Soil and water. Academic Press, New York and London.

Horton, M. L., L. N. Namken, and J. T. Ritchie. 1970. Role of plant canopies in evapotranspiration. p. 301-338. In Evapotranspiration in the Great Plains. Great Plains Agricultural Council, Publication No. 50, Kansas State University, Manhattan.

Jackson, R. D., and S. B. Idso. 1969. Ambient temperature effects in infrared thermometry. Agron. J. 61:324-325.

Kelley, W. P. 1964. Review of investigations on cation exchange and semiarid soils. Soil Sci. 97:80-88.

Ketellaper, H. J. 1963. Stomatal physiology. Ann. Rev. Plant Physiol. 14:249-270.

Kramer, P. J. 1963. Water stress and plant growth. Agron. J. 55:31-35.

LaRue, M. E., D. R. Nielsen, and R. M. Hagan. 1968. Soil water flux below a ryegrass root zone. Agron. J. 60:625-629.

Lemon, E. R. 1960. Photosynthesis under field conditions. II. An aerodynamic method for determining the turbulent carbon dioxide exchange between the atmosphere and a corn field. Agron. J. 52:697-703.

List, R. J. 1958. Smithsonian meteorological tables. Smithsonian Misc. Coll., Vol. 114. Published by the Smithsonian Institution, Washington, D. C.

Marshall, T. J., and C. G. Gurr. 1954. Movement of water and chlorides in relatively dry soil. Soil Sic. 77:147-152.

McGuinness, J. L., and E. F. Bordne. 1972. A comparison of lysimeter-derived potential evapotranspiration with computed values. ARS, USDA Tech. Bull. No. 1452.

Meyer, B. S., D. B. Anderson, and R. H. Bohning. 1960. Introduction to plant physiology. D. Van Nostrand Company, Inc., Princeton, New Jersey.

Miller, D. E., and J. S. Aarstad. 1971. Available water as related to evapotranspiration rates and deep drainage. Soil Sci. Soc. Amer. Proc. 35:131-134.

Miller, R. J., J. W. Biggar, and D. R. Nielsen. 1965. Chloride displacement in Panoche clay loam in relation to water movement and distribution. Water Resour. Res. 1:63-73.

Monteith, J. L., G. Szeicz, and P. E. Waggoner. 1965. The measurement and control of stomatal resistance in the field. J. Appl. Ecol. 2:345-355.

Nielsen, D. R., R. D. Jackson, J. W. Cary, and D. D. Evans, Eds. 1970. Soil water. Western Regional Research Technical Committee W-68, Water Movement in Soils.

Penman, H. L. 1948. Natural evaporation from open water, bare soil, and grass. Proc. Roy. Soc. (London) A. 193:120-145.

Perrier, E. R., and D. D. Evans. 1961. Soil moisture evaluation by tensiometers. Soil Sci. Soc. Amer. Proc. 25:173-175.

Pruitt, W. O., and F. J. Lourence. 1968. Correlation of climatological data with water requirements of crops. Water Science and Engineering Paper No. 9001, Department of Water Science and Engineering, University of California, Davis.

Ritchie, J. T., and E. Burnett. 1968. A precision weighing lysimeter for row crop water use studies. Agron. J. 60:545-549.

Ritchie, J. T., and E. Burnett. 1971. Dryland evaporative flux in a subhumid climate: II. Plant influences. Agron. J. 63:56-62.

Robins, J. S., W. O. Pruitt, and W. H. Gardner. 1954. Unsaturated flow of water in field soils and its effect on soil moisture investigations. Soil Sci. Soc. Amer. Proc. 18:344-347.

Rose, C. W. 1966. Agricultural physics. Pergamon Press, New York.

Rose, C. W., and W. R. Stern. 1965. The drainage component of the water balance equation. Australian J. Soil Res. 3:95-100.

Rosenberg, N. J. 1969. Seasonal patterns in evapotranspiration by irrigated alfalfa in the central Great Plains. Agron. J. 61:879-886.

Rosenberg, N. J., H. E. Hart, and K. W. Brown. 1968. Evapotranspiration - review of research. Nebraska Agr. Exp. Sta. Misc. Bull. 20.

Rosenberg, N. J., and W. L. Powers. 1970. Potential for evapotranspiration and its manipulation in the Plains region. p. 275-299. In Evapotranspiration in the Great Plains. Great Plains Agricultural Council, Publications No. 50, Kansas State University, Manhattan.

Skidmore, E. L., H. S. Jacobs, and W. L. Powers. 1969. Potential evapotranspiration as influenced by wind. Agron. J. 61:543-546.

Slatyer, R. O. 1967. Plant-water relationships. Academic Press, New York.

Slatyer, R. O., and W. R. Gardner. 1965. Overall aspects of water movement in plants and soils. p. 113-129. In The state and movement of water in living organisms. Academic Press Inc., New York.

Spiegel, M. R. 1961. Theory and problems of statistics. Schaum Publishing Co., New York.

Steel, R. G. D., and J. H. Torrie. 1960. Principles and procedures of statistics. McGraw-Hill Book Co., Inc., New York.

Stone, L. R., M. L. Horton, and T. C. Olson. 1973a. Water loss from an irrigated sorghum field: I. Water flux within and below the root zone. Agron. J. 65: (in press).

Stone, L. R., M. L. Horton, and T. C. Olson. 1973b. Water loss from an irrigated sorghum field: II. Evapotranspiration and root extraction. Agron. J. 65: (in press).

Stone, L. R., T. C. Olson, and M. L. Horton. 1973c. Unsaturated hydraulic conductivity for water management measured *in situ.* So. Dak. Acad. Sci. 52: (in press).

Szeicz, G., G. Endrodi, and S. Tajchman. 1969. Aerodynamic and surface factors in evaporation. Water Resour. Res. 5:380-394.

Szeicz, G., and I. F. Long. 1969. Surface resistance of crop canopies. Water Resour. Res. 5:622-633.

Tanner, C. B. 1960. Energy balance approach to evapotranspiration from crops. Soil Sci. Soc. Amer. Proc. 24:1-9.

Tanner, C. B., and W. L. Pelton. 1960. Potential evapotranspiration estimates by the approximate energy balance method of Penman. J. Geophys. Res. 65:3391-3413.

Van Bavel, C. H. M. 1961. Lysimetric measurements of evapotranspiration rates in the eastern United States. Soil Sci. Soc. Amer. Proc. 25:138-141.

Van Bavel, C. H. M. 1966. Potential evaporation: The combination concept and its experimental verification. Water Resour. Res. 2:455-467.

Van Bavel, C. H. M., K. J. Brust, and G. B. Stirk. 1968a. Hydraulic properties of a clay loam soil and the field measurement of water uptake by roots: II. The water balance of the root zone. Soil Sci. Soc. Amer. Proc. 32:317-321.

Van Bavel, C. H. M., and W. L. Ehrler. 1968. Water loss from a sorghum field and stomatal control. Agron. J. 60:84-86.

Van Bavel, C. H. M., F. S. Nakayama, and W. L. Ehrler. 1965. Measuring transpiration resistance of leaves. Plant physiol. 40-535-540.

Van Bavel, C. H. M., and R. J. Reginato. 1965. Precision lysimetry for direct measurement of evaporative flux. p. 129-135. Methodology of Plant Ecophysiology. Proc. Montpellier Symp., UNESCO.

Van Bavel, C. H. M., G. B. Stirk, and K. J. Brust. 1968b. Hydraulic properties of a clay loam soil and the field measurement of water uptake by roots: I. Interpretation of water content and pressure profiles. Soil Sci. Soc. Amer. Proc. 32:310-317.

Veihmeyer, F. J., and A. H. Hendrickson. 1949. Methods of measuring field capacity and wilting percentages of soils. Soil Sci. 68:75-94.

Wadleigh, C. H. 1964. Fitting modern agriculture to water supply. p. 8-14. In Research on Water. Amer. Soc. Agron. Special Publication No. 4. Soil Sci. Soc. Amer., Madison, Wisc.

Westin, F. C., G. J. Buntley, W. C. Moldenhauer, and F. E. Shubeck. 1954. Soil survey of Spink County South Dakota. South Dakota Agr. Exp. Sta. Bull. No. 439.

Wetselaar, R. 1961. Nitrate distribution in tropical soils: II. Extent of capillary accumulation of nitrate during a long dry period. Plant Soil 15:121-133.

Wetselaar, R. 1962. Nitrate distribution in tropical soils: III. Downward movement and accumulation of nitrate in the subsoil. Plant Soil 16:19-31.

Wiegand, C. L., and L. N. Namken. 1966. Influences of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature. Agron. J. 58:582-586.

Willardson, L. S., and W. L. Pope. 1963. Separation of evapotranspiration and deep percolation. J. Irrigation and Drainage Division, Amer. Soc. Civil Eng. 89:77-88.